Industry-Wide Database for Power Transformers

Decision Support for Substation Asset Management

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Technical Update, December 2012

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ABSTRACT

Asset managers need meaningful, defensible metrics to understand the implications of aging transformers and make informed decisions regarding maintenance, repair, and replacement of these high-dollar assets. To ensure that these meaningful metrics are established using the best available data, EPRI is developing an Industry-Wide Database (IDB) for power transformers.

The IDB is a repository of detailed performance data on transformers pooled from supporting utilities. The IDB captures data from multiple sources in a common format for data mining and statistical analysis. Data is obtained on in-service transformers and those removed from service due to failure or retirement. The data are historically accurate and include failure mode, operational and repair history, and equipment design information.

The IDB provides participants with aggregated data and information resources not available to individual utilities to assist in developing asset management strategies for aging substation transformer fleets. It enables statistically valid analysis to better determine equipment failure rates, identify “bad actors” early, and help identify best maintenance and specification practices.

Ultimately, the IDB is a decision-support resource that provides information for business cases to illuminate the costs and benefits of transformer management options such as repair, replacement, or refurbishment. It provides a rational, quantitative basis for asset management decisions that improve service reliability and return on investment.

Using the IDB and advanced statistical analysis techniques, EPRI has begun developing hazard rate functions for selected transformer groups. These functions are based on the largest known depository of utility power transformer performance data and provide insights not available elsewhere. A number of utilities have used the IDB to assess their fleet performance and to help plan capital and spares policies.

This report summarizes the IDB’s development, application as a decision support tool for asset managers, data categories and data processing, insights on transformer aging and failure, and utility applications.

Keywords

Power Transformers
Asset Management
Industry-wide Database

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1
OVERVIEW AND EXECUTIVE SUMMARY

This chapter provides an overview and summary of EPRI's Power Transformer Industry-wide Database and some real-world utility application examples. Later chapters provide more detailed description.

Introduction

Managing fleets of aging assets is a critical challenge for utility companies striving to maintain reliability and control costs in a constrained business environment. Transformer fleet management is an especially important subject for many utilities operating populations of power transformers that have significant numbers of units at or beyond their typically assumed economic lives. Because a high percentage of transformers are approaching or even exceeding age forty, existing methods and a reliance on past performance may not be adequate for the effective management of this generation of transformers. Consequently, developing and justifying a repair/refurbish/replace management strategy for such populations and the rational basis for it, is a critical need.

Traditionally, utilities based transformer maintenance and replacement decisions on the assumption that future performance, including failure rates, would be similar to historic experience. This approach served the industry well in the past but recent concerns, including adverse demographic distributions common in many utilities, limited maintenance resources, and increased demand for service reliability, have led to new asset management approaches. Today, effective maintenance and asset management decisions that maximize performance and minimize costs should be based on the best available assessments of risks associated with actual transformer condition and expected future performance.

Predicting the failure rate of transformers nearing the end of their design life is challenging, making typical asset management activities such as repair and replacement decisions more difficult. Generic transformer reliability data may not be adequate to inform such decisions, and data from a single company may not be extensive or diverse enough for useful statistical analysis. To help utilities better predict transformer service life, EPRI created the Transformer Industry-Wide Database (IDB). The IDB pools transformer operating and failure data from supporting utilities in order to assemble a statistically valid population that includes a variety of power transformers.

Using the IDB and advanced statistical analysis techniques, EPRI has begun developing hazard rate functions for selected transformer groups. These functions are based on the largest known depository of utility power transformer performance data and provide insights not available elsewhere. A number of utilities have used the IDB to assess their fleet performance and to help plan capital and spares policies.

IDB: Decision Support for Substation Asset Management

Industry-wide equipment performance databases (IDBs) are a means for establishing a broad based repository of equipment performance data. With proper care and analysis, these data can provide information about the past performance of equipment groups and subgroups and the factors that influence that performance. With enough data, projections can be made about future performance. Both past and future performance information can be useful for operations, maintenance, and asset management decisions. Collection and analysis of IDB data can provide information about the differences in performance of various equipment subgroups as well as inputs for developing hazard rate curves and parameters for life expectancy models.

Collecting transformer performance and failure data in a common format from many utility sources has established a database that allows broad based analysis to better determine equipment failure rates, identify "bad actors" early, and help identify best maintenance and specification practices. A well established Database helps utilities with early risk detection and risk-informed maintenance and asset management decision based on industry wide transformer performance and failure data. This initiative provides participating utilities with data and information resources, not currently available to an individual utility, to assist in developing a repair/refurbish/replace strategy for their aging transformer fleets.

Ultimately, the IDB is a decision-support resource that provides information for business cases to illuminate the costs and benefits of transformer management options. It provides a rational, quantitative basis for asset management decisions that improve service reliability and return on investment.

Asset managers need meaningful, defensible metrics to understand the implications of aging transformers and make informed decisions regarding maintenance, repair, and replacement of these high-dollar assets. EPRI developed the Industry-Wide Database for power transformers to ensure that these meaningful metrics are established using the best available data,.

Both past and projected performance information can support an array of critical decisions associated with investment planning, strategic asset management, maintenance optimization, and more. Examples of these decisions and related IDB support include the following:

- Maintenance scheduling—what and when?
    - Better equipment failure models to forecast condition degradation
- Repair or replace decisions
    - More quantitative assessments of risk
- Capital planning
    - Improved forecasts of annual equipment budgets and failures
- Reliability standards compliance
    - Accurate and broad based historical industry performance

Data Categories

The sharing of failure and trouble experiences on a detailed and confidential basis is necessary in order for the industry to build advanced predictive models and to better determine the expected lives of critical assets. The IDB is a repository of detailed performance data on transformers pooled from supporting utilities. The IDB captures data from multiple sources in a common format for data mining and statistical analysis. The data are historically accurate and include failure mode, operational and repair history, and equipment design information.

The database specification includes physical asset information, trouble and failure events for use in life assessment and component analysis. The specification also allows the database to be used in maintenance and asset management optimization – including strategies for replacement and to identify design and material problems.

The IDB includes population and failure data sets based on transformer type, make, model, application, and age. There are two broad classes of transformer data included: in service units (current population data) and units permanently removed from service due to failure or retirement. Data collection for the IDB began in 2006, and the database now has records on about 40,000 power transformers. Several thousand more records are in various stages of review for inclusion.

- Raw data supplied to date:
  - In-service Units: **36626**
  - Failure Records: **2958**
- Mapped data set:
  - In-service Units: **33410**
  - Failure Records: **2587**
- Processed data set:
  - In-service Units: **20388**
  - Failure Records: **2121**
- Data used for Service History Analysis:
  - In-service Units: **16787**
  - Failure Records: **1863**

Table 1-1
IDB Data at a Glance

Transformer Demographics and Life Expectancy

Many substation transformers were installed in the 1960s and 1970s and are approaching the end of their nominal design lives. Figure 1-1 below shows a typical age profile for over 7,000 units in a particular subset of in-service transformers contained in the transformer IDB. Clearly depicted is the “asset wall” in the 35 to 45 year age bracket. This IDB data is aggregated from eight utilities with a variety of fleet sizes and service territories and is thought to be representative of the general industry in North America.

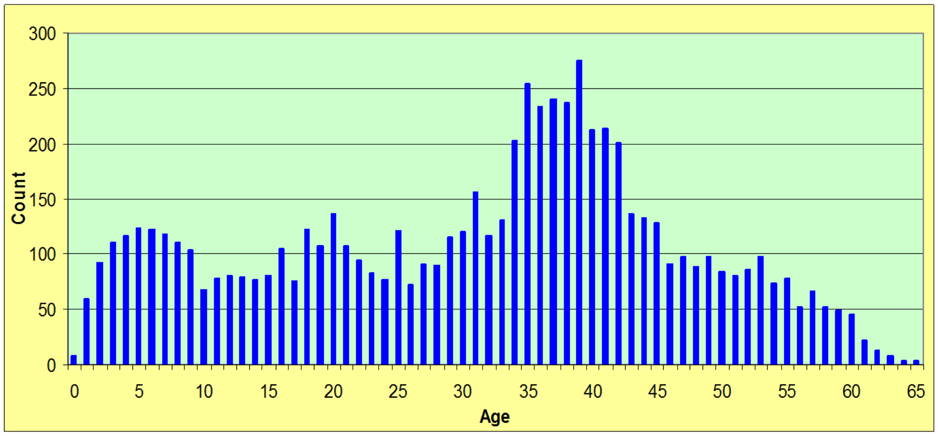

Figure 1-1
Typical Age Profile: In-Service Transformers

Like other types of equipment, transformers may follow a failure rate pattern similar to the familiar bathtub curve—an initially high rate of infant mortality failures, followed by a relatively low and constant failure rate during a long service life, then an increase in wear-out failures with impending end of life as depicted in Figure 1-2.

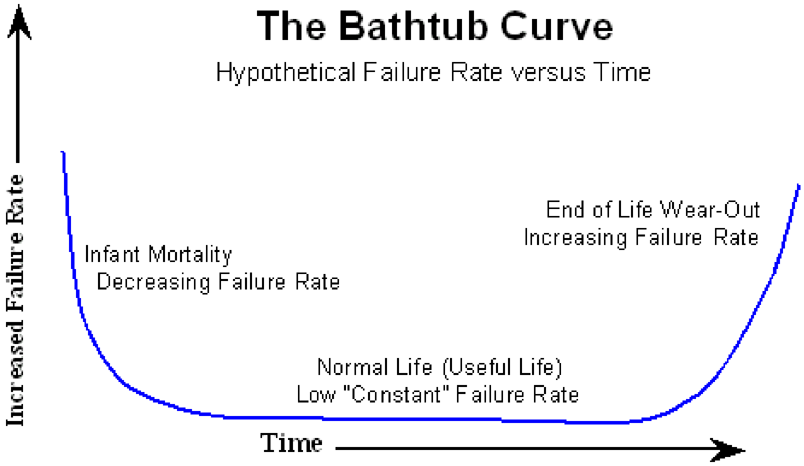

Figure 1-2
Failure Rate Over Time

Insights on Transformer Aging and Failure

One application of the IDB is to assess whether this curve accurately describes historical transformer performance. If the bathtub curve applies to transformer life,

- What are the parameters of the curve—especially the wear-out portion of the curve?
- Do the curve parameters change with different transformer makes, models, vintages, and applications?

Answering these questions is more important than ever as transformer fleets age and high replacement costs and uncertain lead times put more pressure on asset managers striving to meet high reliability standards. Figure 1-3 shows the relationship between a fleet demographic profile and a possible failure rate curve. As can be readily seen, the position of the asset wall relative to the point of increasing failure rates, the "back end" of the bathtub curve, will determine the number of expected failures. Understanding the failure rate parameters is a major objective of the IDB work.

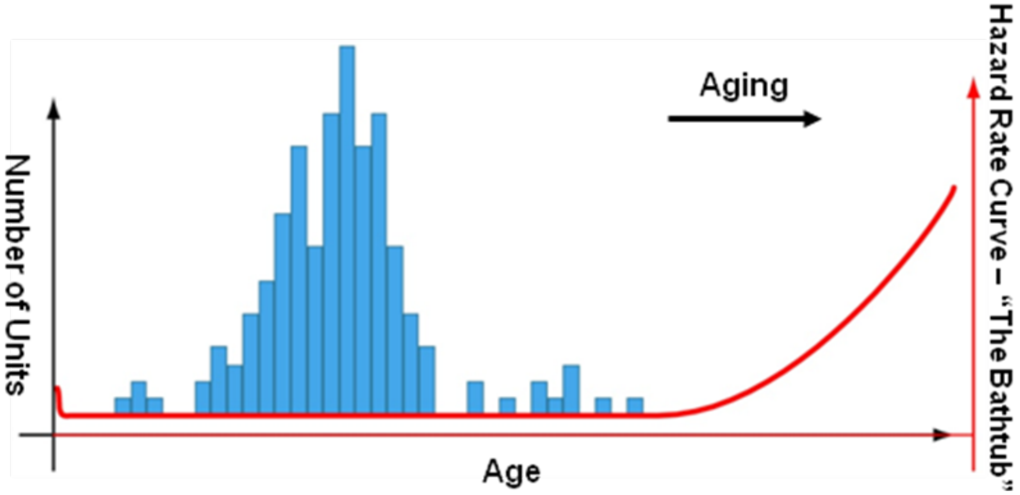

Figure 1-3
Relationship between Hypothetical Demographics and Failure Rate Curve

Insights on Transformer Maintenance

Analysis of IDB failure records has also provided insights about failure causes and transformer component failure performance. This information can help maintenance managers develop proactive programs that may reduce maintenance costs and increase service life. Figure 1-4 shows the failure classification taxonomy. Additional information on failure characterization is provided in Chapter 2.

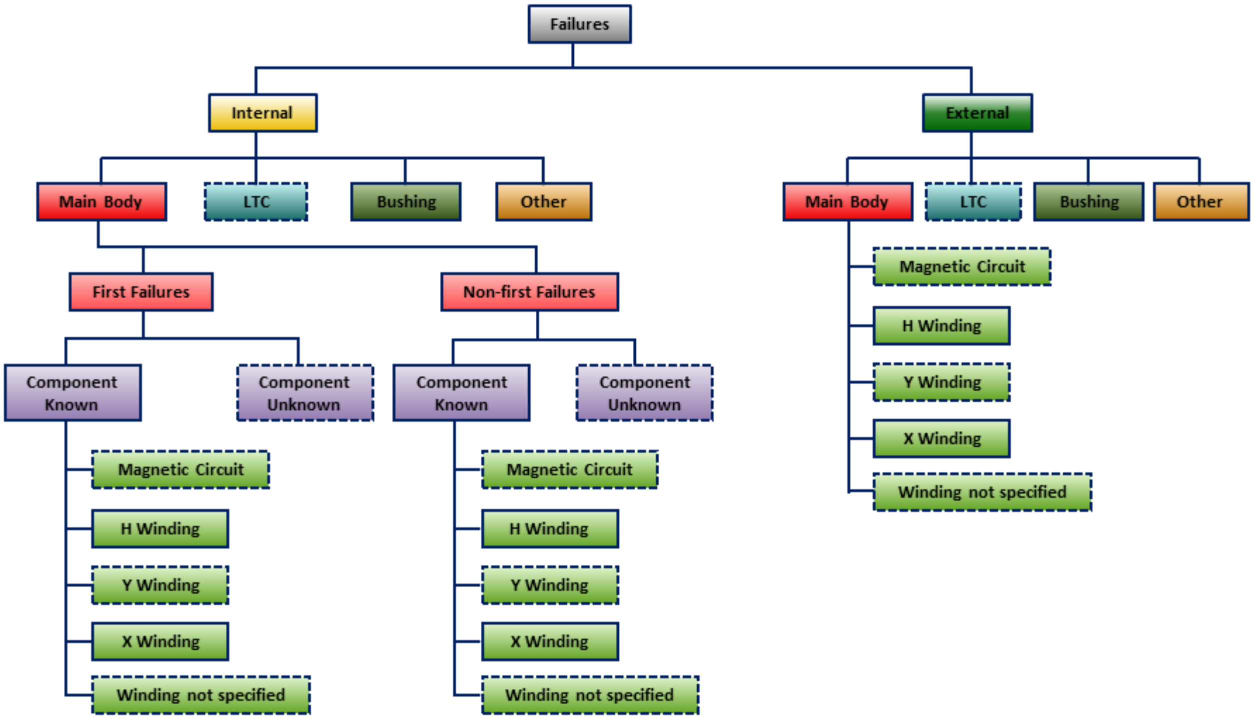

Figure 1-4
Failure Detail Classifications

Utility Applications

The IDB supports two key utility asset management goals

1. Minimize lifecycle-cost of equipment operation, maintenance and replacement with defined risk
2. Make operations, maintenance, and asset management decisions using analytics based upon risk associated with actual equipment and the equipment's historical and expected performance.

These capabilities support improvements in investment planning, strategic asset management, maintenance optimization, and more.

Forecasting Failures

One goal of the IDB work is to develop appropriate hazard rates for transformer subsets of interest. The hazard functions can be convoluted with the corresponding in-service population to provide forecasts of anticipated failures.

In Figure 1-5, an application example for a set of transformers from a particular utility provides the probability distribution of the number of failures in the next year based on a hazard rate determined from IDB analysis. Also provided are 95% confidence bounds on these probabilities. For example, the expected probability of having two failures in the next year is about 0.27. The black bars are the upper and lower 95% confidence bounds on this individual probability. That is, there is 95% confidence that the true probability is between about .28 and .21. There is essentially 0% chance of having greater than nine failures in the next year for this population.

These results were computed using the appropriate hazard function and the transformer set demographic data. Such calculations can provide information useful for asset management and capital planning.

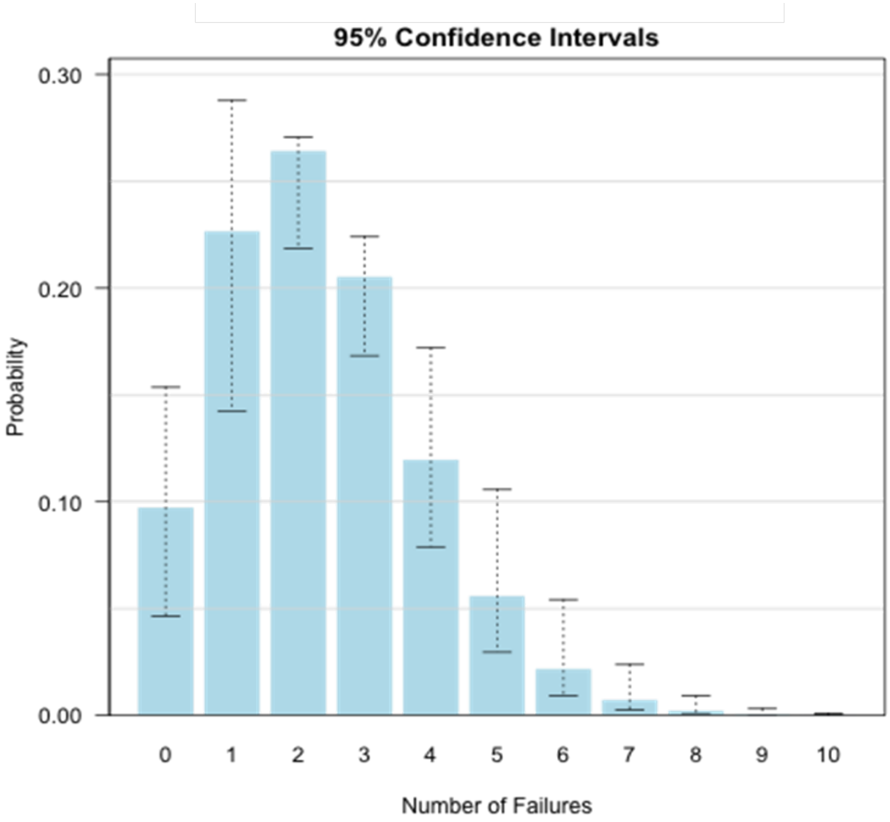

Figure 1-5
Application Example: Yearly Failure Projections

Two additional application examples where utilities have applied the Transformer IDB to develop new insights and actionable information about their transformer fleets are summarized below.

Utility A

Utility A sought to develop a year-by-year prediction of the expected number of failures for the company's 67 kV family of substation transformers for the next five years to help with capital planning and spares strategy. Because of their aging fleet, management was not willing to rely on historical failures.

The projections were based on advanced life analysis techniques developed in the IDB project. The analysis used IDB data and observations from similar transformers from other utilities and Utility A's in-service and historical data, which was mapped into the EPRI IDB data model with extensive utility interaction and support.

The analysis encompassed and accounted for four classifications of failure modes
(see Figure 1-4):

1. Internal main body failures,
2. Internal non-main body failures,
3. External main body failures,
4. External non-main body failures.

The project team used Bayesian survival analysis with appropriate utility data for each failure mode to determine hazard function for that mode. The resulting failure functions and in-service population were utilized in a Monte Carlo simulation to predict the number of failures of the currently in service transformers for each of the next five years. Figure 1-6 shows the predicted number of failures of the currently in-service transformers for each of the next five years.

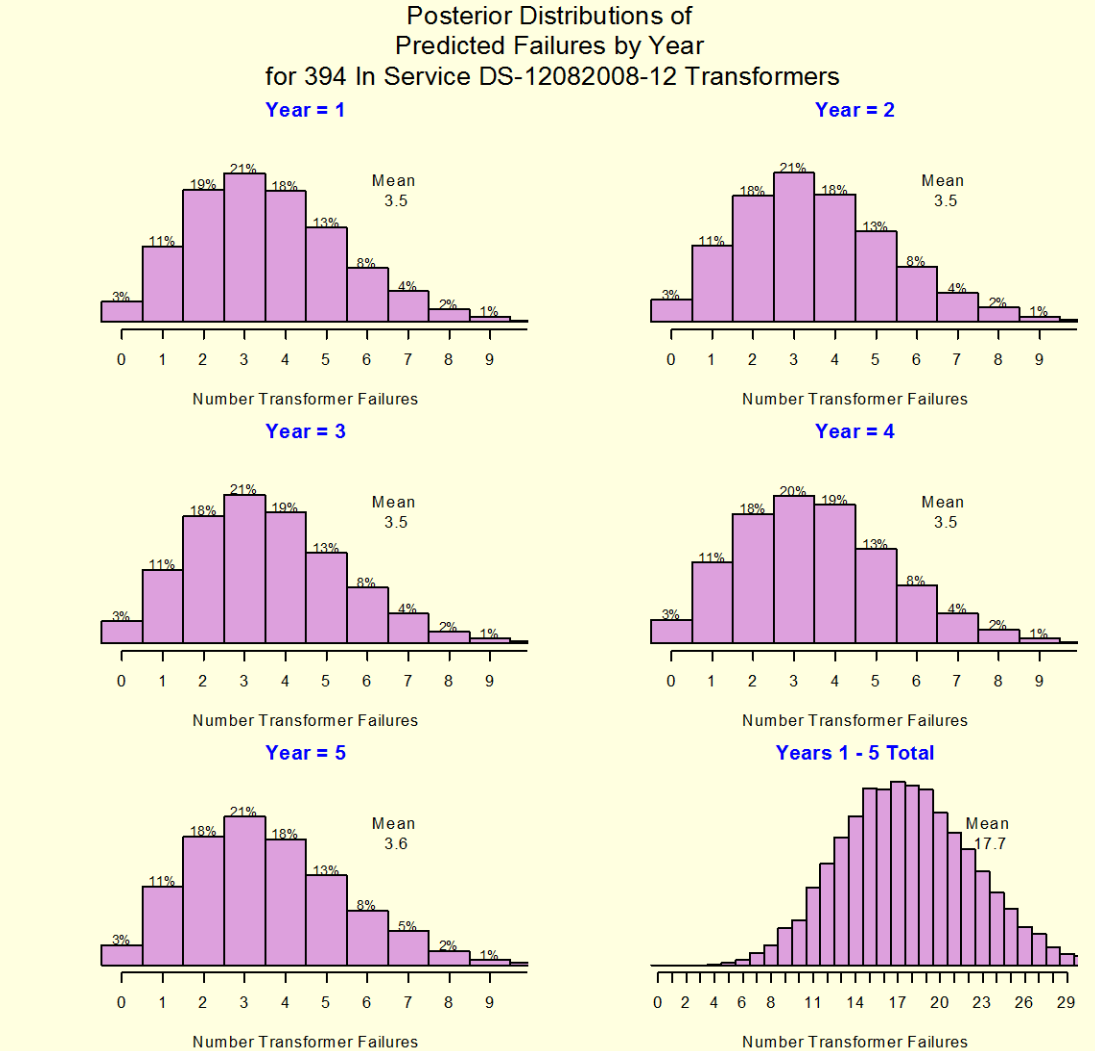

Figure 1-6
Predicted In-Service Transformer Failures for Each of the Next Five Years

Utility B

Utility B management wanted to understand how its transformer fleet's age and failure rates compared with other utilities. EPRI's response was to use IDB data and develop several views, as follows:

- Yearly average age
- Fleet composition
- Yearly failure rate
- Running failure rate

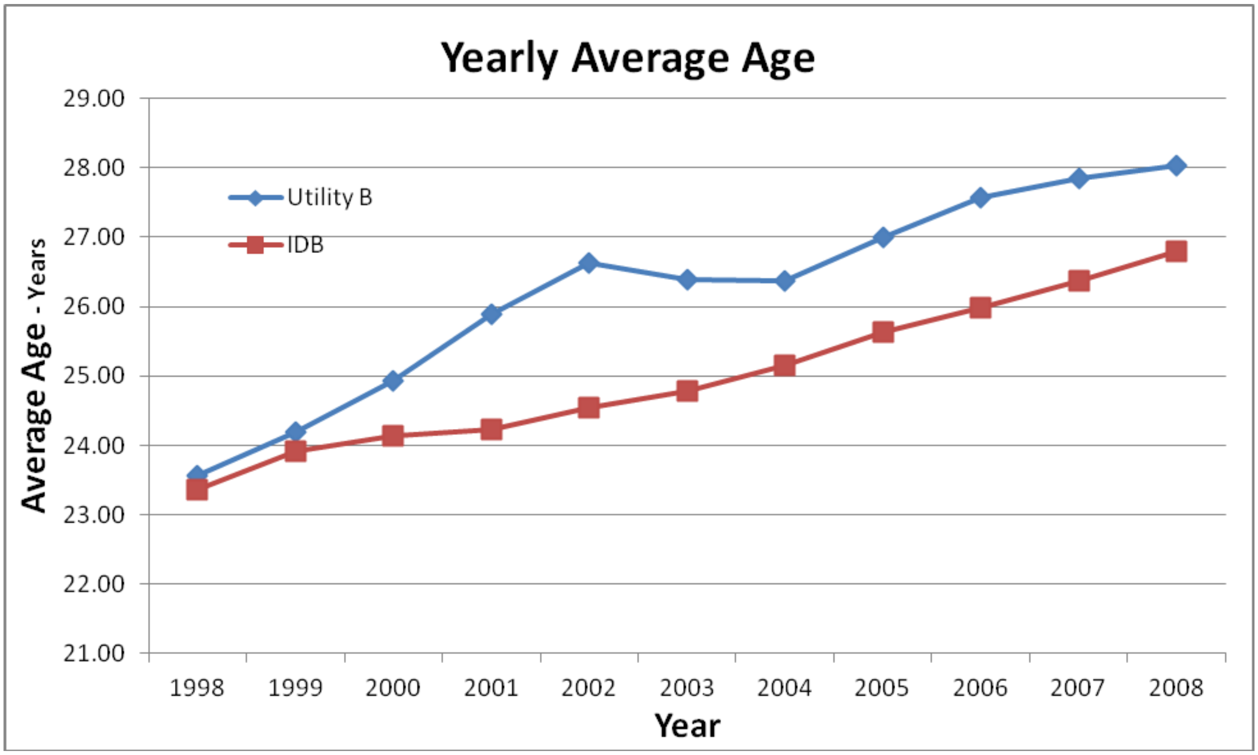

Figure 1-7
Yearly Average Age, Utility B and IDB

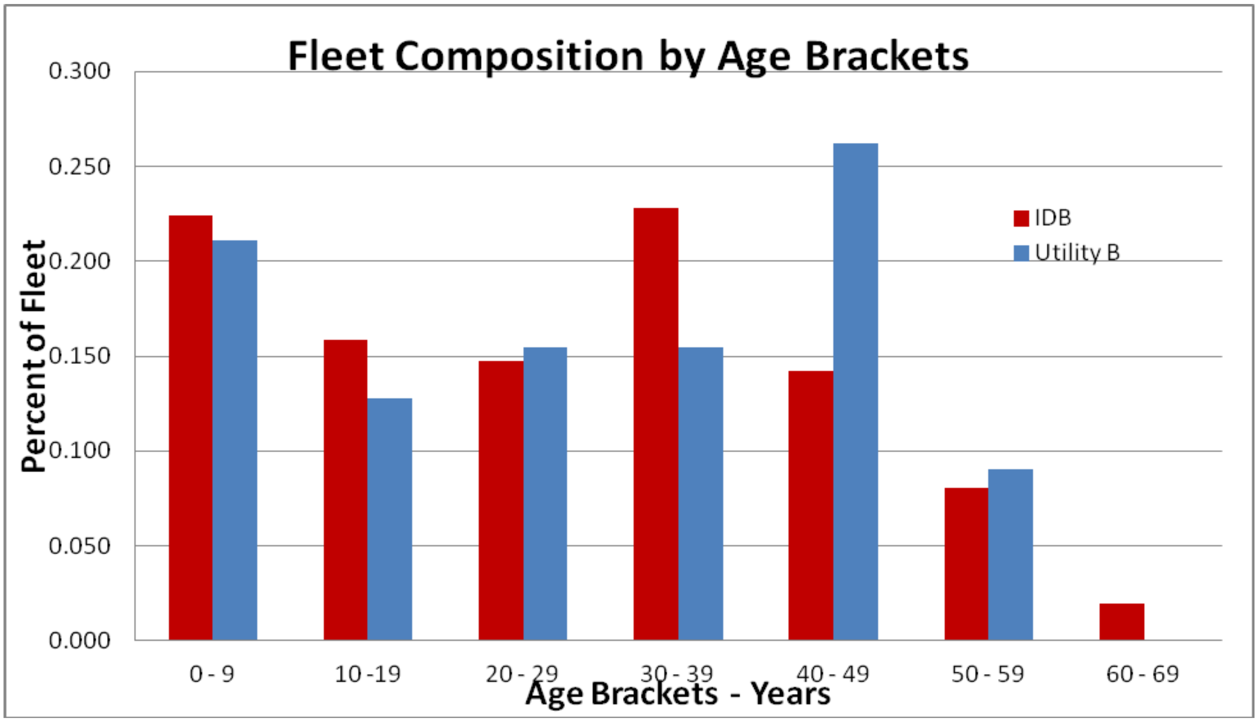

Figure 1-8
Fleet Composition by Age Brackets, Utility B and IDB

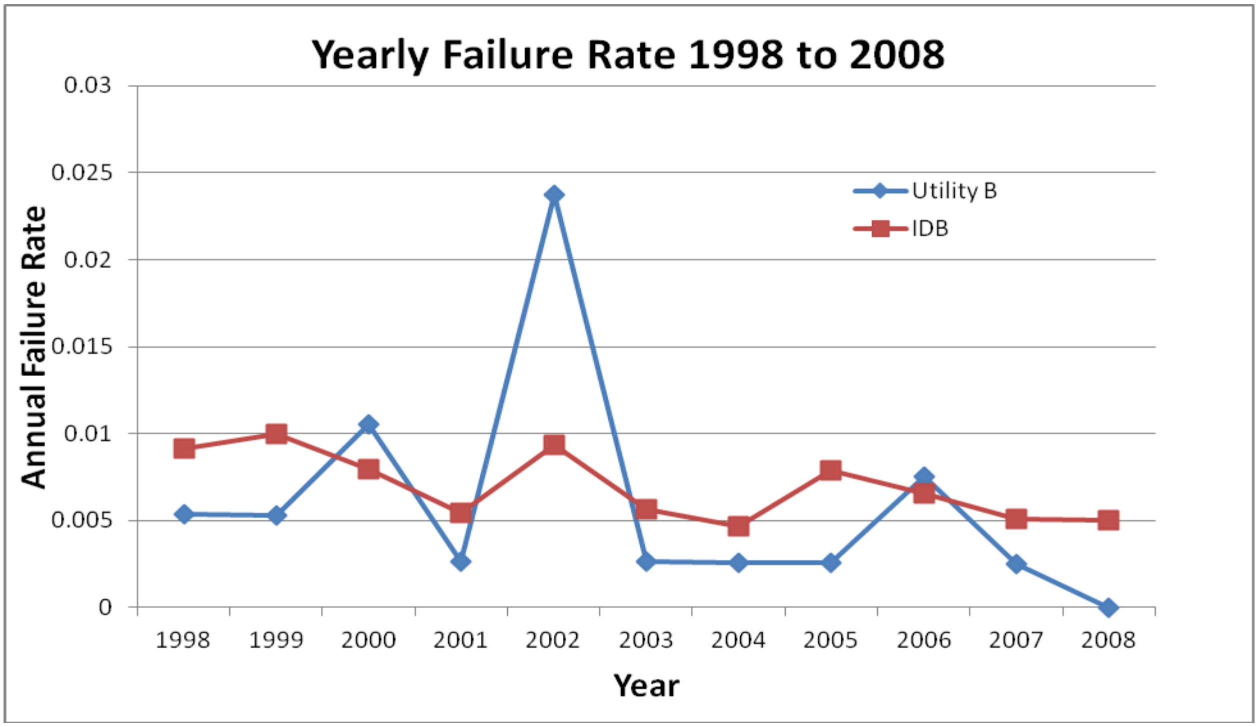

Figure 1-9
Yearly Failure Rate, Utility B and IDB

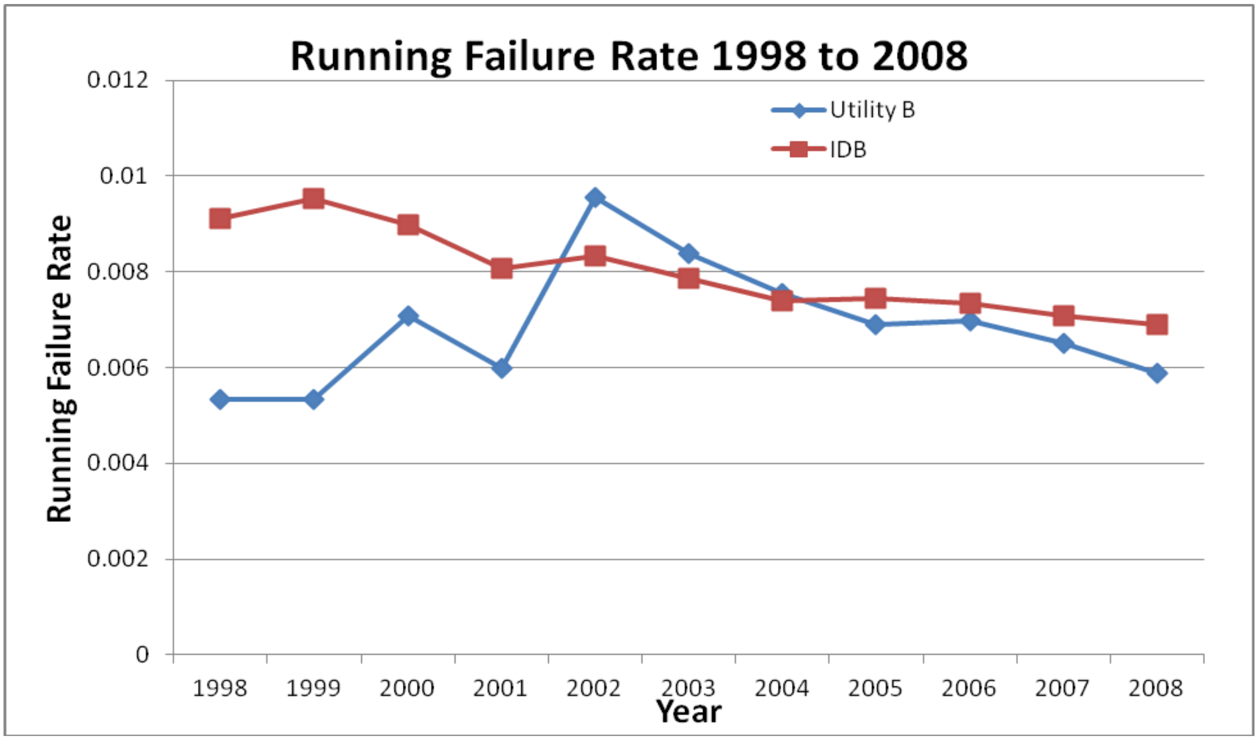

Figure 1-10
Running Failure Rate, Utility B and IDB

EPRI's analysis graphically showed that Utility B's power transformer fleet failure performance was better than that of the IDB aggregate despite having a somewhat older population.

Conclusions

The development of the IDB has revealed valuable insights into the aging transformer fleet, such as the age distribution and average age of in-service and failed transformers in different voltage classes, failure rates, fleet composition by age brackets, and types and causes of failures by transformer class and component. The IDB provides participants with aggregated data and information resources not available to individual utilities to assist in developing asset management strategies for aging substation transformer fleets. It enables statistically valid analysis to better determine equipment failure rates, identify "bad actors" early, and help identify best maintenance and specification practices. Preliminary results indicate that power transformer failure rates increase more slowly with age than previously speculated and that the "back end" of the bathtub curve is not as steep as generally depicted. Some utilities have already made practical use of the IDB project results.

An Ongoing Effort

EPRI's transformer IDB will provide utilities valuable insights and information to support maintenance repair and replacement decisions, and asset management decisions to minimize lifecycle costs of equipment replacement and maintenance, including failure costs.

The IDB is an ongoing development and the insights, underlying methodology, approach and findings continue to be fine-tuned, enhanced and evolve as new data-sets are added and existing data reviewed. More detailed description is provided in the following chapters. The reader is also directed to the below references.

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2

TRANSFORMER IDB: DESCRIPTION AND DEVELOPMENT

This chapter provides an overview of the Transformer Industry-wide Database supporting research and development, and data characteristics.

Overview

Managing fleets of aging power transformers is a critical issue for utility companies striving to maintain reliability and control costs. Predicting the failure rate of transformers nearing the end of their design life is challenging, making typical asset management activities such as repair and replacement decisions more difficult. Key to robust, risk-based decision making are meaningful metrics supported by equipment failure models and hazard rates, all based on the best available data.

Generic data are insufficient in developing meaningful metrics that can provide performance information on different transformers by family, make, model, application and age. Data from a single company may not be extensive or diverse enough for useful statistical analysis. The sharing of failure and trouble experiences on a detailed and confidential basis is necessary in order for the industry to build advanced predictive models and to better determine the expected lives of critical assets.

The objective of this project is to develop a transformer performance database that can be used by the industry to predict transformer reliability for a variety of risk profiles. EPRI's Industry Wide Performance Database -Transformers models power transformer assets and failures. Included in the database are asset attributes to allow the segregation and analysis by manufacturer, model, application and risk exposure.

Using basic nameplate and failure information, this database tries to overcome the following challenges:

- Generic transformer reliability models are inadequate for complex decision support.
- Company data does not statistically represent diverse asset population subsets.
- Difficult to identify and track performance problems within groups, e.g. design type or age bracket.
    - No easy way to benchmark across companies matching "apples to apples."
    - O/M Practices
    - Design Issues
    - Application

The database specification includes physical asset information, trouble and failure events for use in life assessment and component analysis. The specification also allows the database to be used in maintenance and asset management optimization – including strategies for replacement, to identify design and material problems. The IDB data model is more fully described in Appendix A.

The IDB pools transformer operating and failure data from multiple utilities in order to assemble a statistically valid population that includes a variety of power transformers. The IDB provides participants with aggregated data and information resources not available to individual utilities to assist in developing repair/replace/refurbish strategies for aging substation transformer fleets. The IDB development effort collects equipment performance and failure data in a common format from many sources to establish a database that enables statistically valid analysis to better determine equipment failure rates, identify "bad actors" early, and help identify best maintenance and specification practices. Ultimately, the IDB is a decision-support tool that provides information for business cases to illuminate the costs and benefits of transformer management options. It provides a rational, quantitative basis for asset management decisions that improve reliability and benefit a company's bottom line.

Research & Development

The research and development path of the IDB is as follows:

1. Assess needs through exploratory work to determine data model and analysis requirements
2. Establish common definitions and develop data models to assist with collection of historical in-service and failure data in a common format. These models also help improve utility and industry record-keeping.
3. Collect equipment performance and failure data from participating utilities to develop an industry-wide database. This database is designed to accomplish the following:
    a) Enable statistically valid analysis to determine equipment failure rates and identify at-risk units ("bad actors") early
    b) Enable the development of other meaningful asset management and equipment performance metrics
    c) Provide members with aggregated data and information resources not currently available to individual companies
    d) Provide members with information that is critical in developing repair/replace/refurbish strategies for aging transformer fleets
4. Develop application guidelines on how to analyze data and derive:
    a) Performance characteristics—for example, comparison by different family, make, model, applications and age,
    b) Asset management metrics—for example, failure rates
5. Develop tools to allow utilities to perform analysis:
    a) Calculate observed failure rate,
    b) Calculate descriptive statistics,
    c) Eventually, calculate statistically valid hazard rates and project the anticipated number of failures moving forward.

Risk-Based Decision Support

An advanced risk-based approach to managing transformer assets uses historical performance data to group and rank transformers. This decision support foundation performs four key steps:

- Assessing existing performance,
- Specifying required performance,
- Projecting future performance, and
- Understanding how to bridge gaps

The IDB provides a broad-based repository of transformer performance data as a key part of a decision support foundation. Data is obtained from many utilities on in-service transformers and those removed from service due to failure or retirement. The data are historically accurate and include failure mode, operational and repair history, and equipment design information. The transformer data collection and analysis started in 2006, and now contains records on more than 36,500 in-service and more than 2000 failed power transformers.

With proper care and analysis, this data can provide information about the past performance of equipment groups (e.g., substation transformers) and subgroups (e.g., 345 kV auto transformers) and the factors that influence that performance (e.g., voltage, manufacturer). With enough data, projections can be made about future fleet performance (e.g., expected number of failures), and both past and projected future performance information can be useful for operations, maintenance, and asset management decisions.

Transformer Data Categories

The IDB includes population and failure data sets based on transformer type, make, model, application, and age. There are two broad classes of transformer data included: in-service units (population data) and units permanently removed from service due to failure or retirement. For the purpose of IDB, failure is the termination of a transformer’s ability to perform its functions with acceptable risk without major repair. Note that a failure as defined for the IDB can include:

- Failure with a forced outage
    - Requiring the transformer’s immediate removal from service by relay operation or emergency switching (for example winding fault)
- Failure with a scheduled outage
    - In which the transformer is removed from service at a selected time (for example, due to unacceptably high dissolved gas levels).

Failures recorded in the IDB require either the replacement of a bushing or LTC or the removal of the transformer for replacement or rewind.

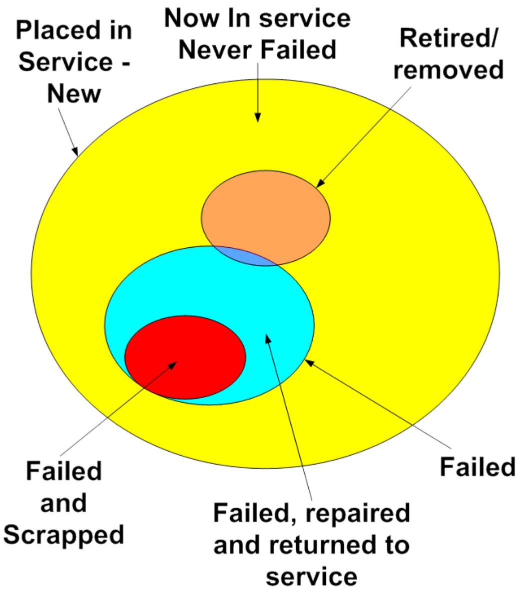


Figure 2-1
IDB Data Categories (not to scale)

In-service population data includes

- Transformer name plate information
- Serial number or unique identifier
- In-service and/or manufactured date
- Application
- Type, e.g., auto, non-auto transformer
- Previous rewind (yes/no, date)
- Service location (utility, substation, transformer position)

Removed from service data includes the preceding information, plus the date and the reason the transformer was removed from service.

Service Status is the status of the unit at the end of its service segment. There are three classifications:

- In-Service Unit (ISU): was installed at the start date and operable at the end date
- Failed In-Service (FIS): was installed at the start date and failed at the end date
- Retired Before Failure (RBF): was installed at the start date and operable at the end date but permanently removed from service, e.g., due to station retirement

Transformers are repairable and can have multiple service segments, in one or more service positions. Units are identified and tracked by a unique serial number, assumed to remain the same throughout the transformer life (but may change after a rewind). Two transformers cannot simultaneously occupy the same service position. Failures occur during service segments, i.e., not observed in spare, not delivered, or storage positions.

Data Processing

In general utility supplied data requires review and cleansing before it is suitable for inclusion in the IDB. Typical issues include:

- Missing serial numbers
- Duplicate serial numbers
- Missing dates
- Limited failure history

Figure 2-2 presents an overview of the IDB process developed. Extensive interaction with the supplying utility is often required to assure sufficient data quality and proper descriptive classification.

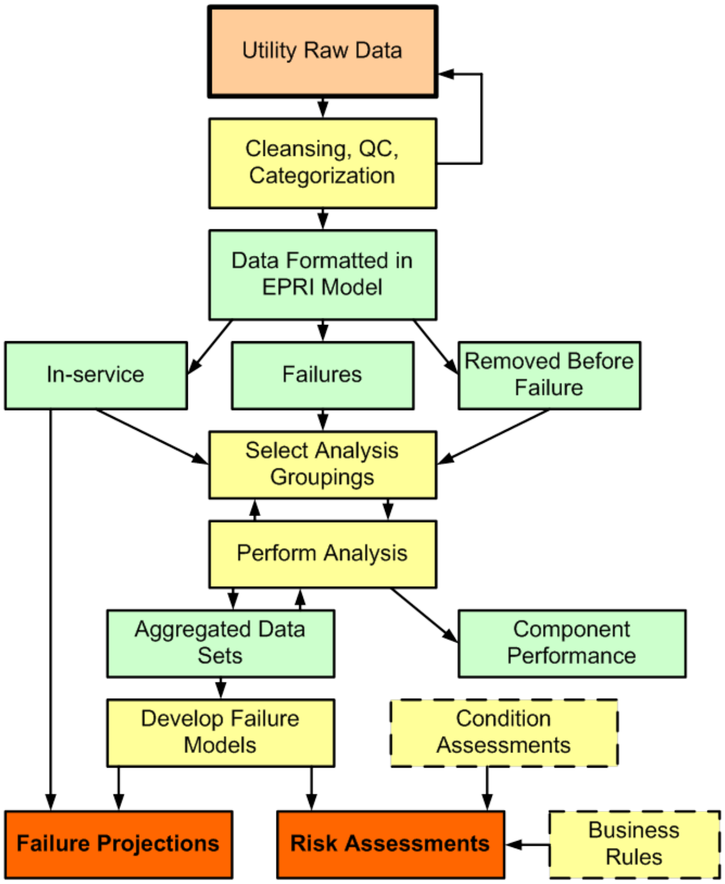


Figure 2-2
The IDB Process

An important application of IDB data is to develop hazard functions (hazard rates) through parametric analysis. This involves fitting a model to the data in order to mathematically describe the transformer aging and wear-out process over time. Since transformers have different designs, different components, and fail for different reasons, analysis groups of similar transformers must be properly selected to develop failure models appropriate for each group. Data must also be assigned to the correct group—auto transformers must be grouped with auto transformers and rewound units grouped with rewound units. Determining the appropriate groupings was an important accomplishment of the analysis work.

Grouping transformer populations into subsets of similar units with shared characteristics and behavior is essential to enable an "apples to apples" analysis. The need for such groupings is illustrated by the notable differences in survival performance between new and repaired units and between auto and non-auto units (Figure 2-3) demonstrated by a particular subset of the IDB. Analysis groups must be properly selected to develop failure models appropriate for each group.

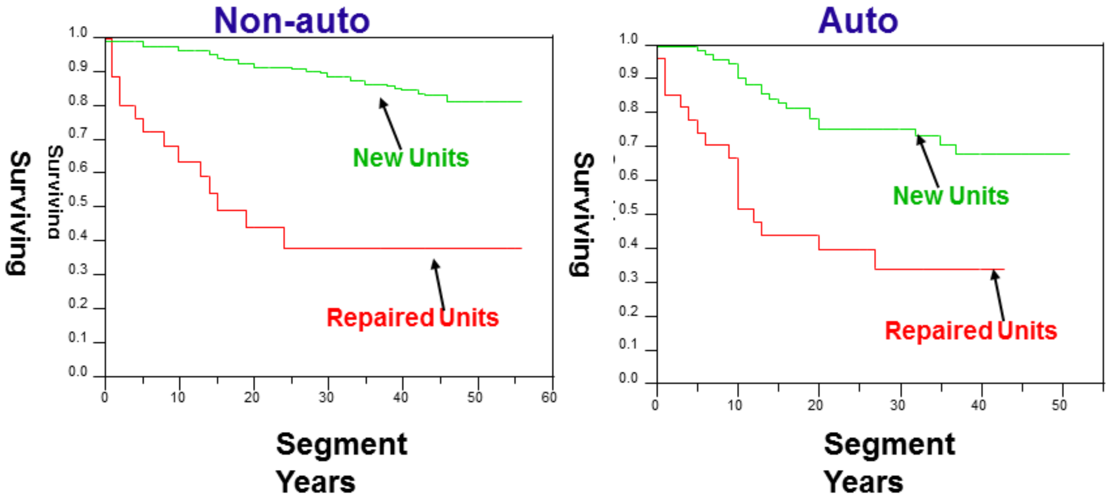


Figure 2-3
Survival Plots for New versus Repaired Units—Notable Differences in Performance

Failure data details are also required in defining sub-groupings, including failure location (main body, load tap changer, bushing) and cause (internal or external to the transformer system). Because the models under initial development focus on the wear-out portion of the bathtub curve, the work is primarily concerned with failures that could be wear-out related. Therefore, main body failures initiated by external events such as a stuck breaker or mis-operating relay are identified and analyzed separately. To model wear-out, only failures beyond the expected age for inception of wear-out are used for analysis. Load tap changers and bushings can be expected to wear-out at different rates from each other and from the main body and therefore also are analyzed separately, even if their failure results in failure of the transformer.

There are additional characteristics of the available data that also must be taken into consideration.

- Failure data is right and left censored
  - Not all failure dates have been recorded
  - Not all transformers have failed

- Failure data is truncated
    - Not all failures are recorded

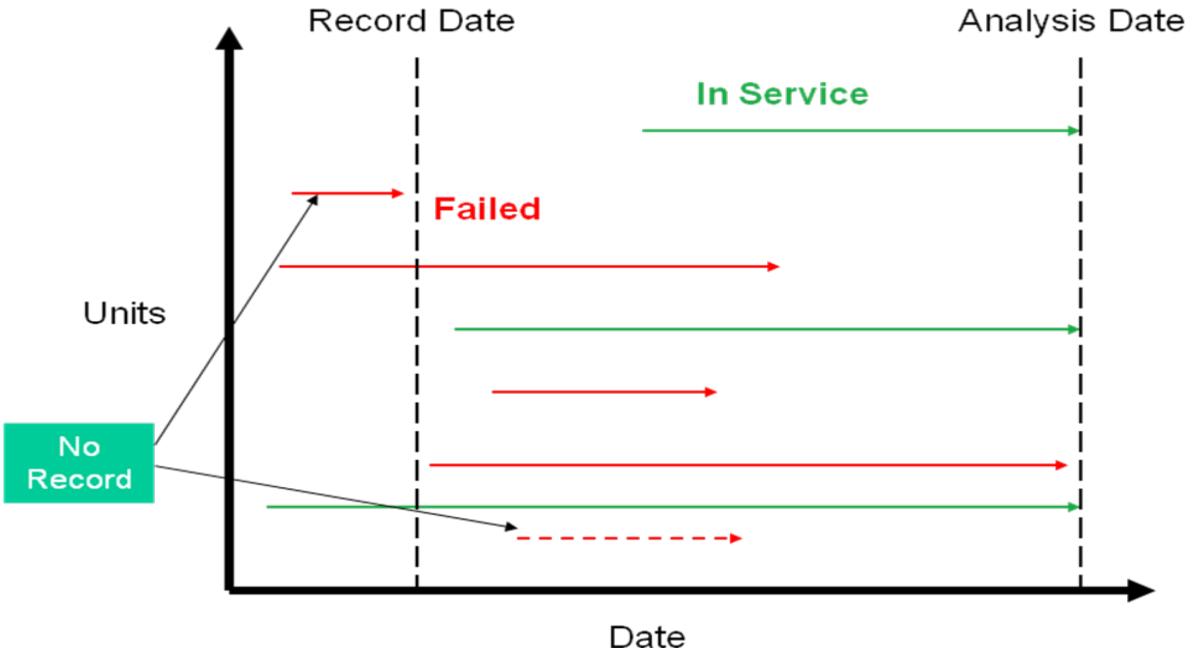


Figure 2-4
Data Characteristics

Because of these characteristics, care must be exercised in selecting and applying the analytical methods used.

The complete data record desired for analysis is:

For each in-service entry

- Serial or ID number
- Nameplate
- Installation date
- Application
- Auto Y/N
- Rewound Y/N

For each failure above plus

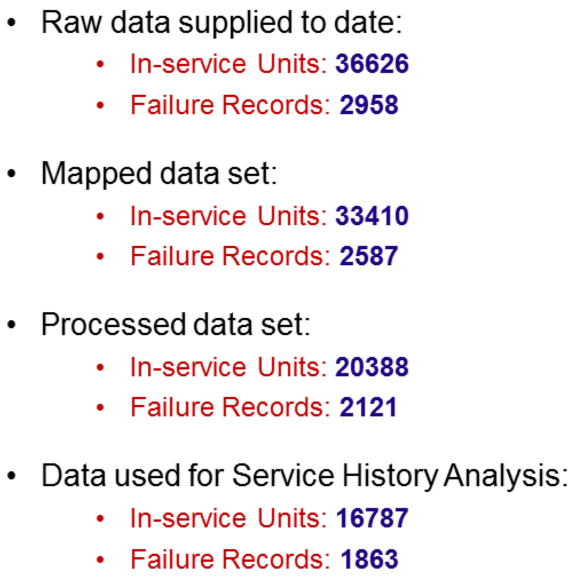
- Failure date
- First failure Y/N
- External cause Y/N

- Main body Y/N

For each data set

- Right censoring date
- Left censoring date
- Wear-out start age

Data collection for the IDB began in 2006, and the database now contains records on about 40,000 power transformers, as shown in Table 2-1. Several thousand more records are in various stages of review for inclusion.



- Raw data supplied to date:
  - In-service Units: **36626**
  - Failure Records: **2958**
- Mapped data set:
  - In-service Units: **33410**
  - Failure Records: **2587**
- Processed data set:
  - In-service Units: **20388**
  - Failure Records: **2121**
- Data used for Service History Analysis:
  - In-service Units: **16787**
  - Failure Records: **1863**

Table 2-1
IDB Data at a Glance

3

DATA ANALYSIS AND RESULTS

Demographic Analysis

The large amount of information contained in the IDB allows for many different types of demographic analyses. These can be useful for understanding the statistical IDB results and for making comparisons between a utility's fleet data and the IDB. Several example plots are provided below.

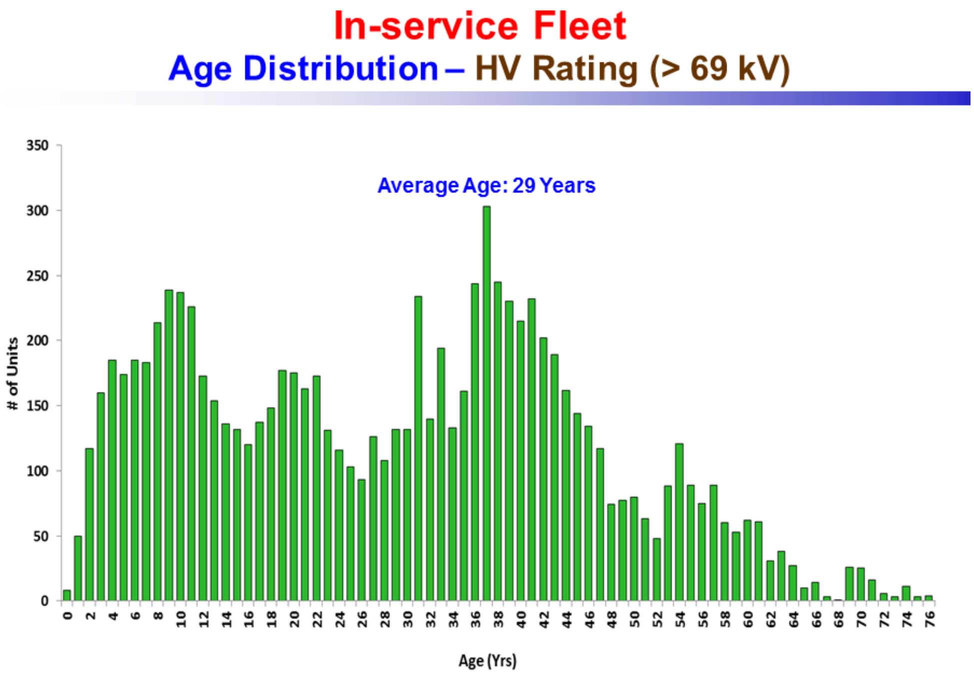


Figure 3-1
Profile of Aging Transformers: Age Distribution of In-Service Transformers 69kV and Above

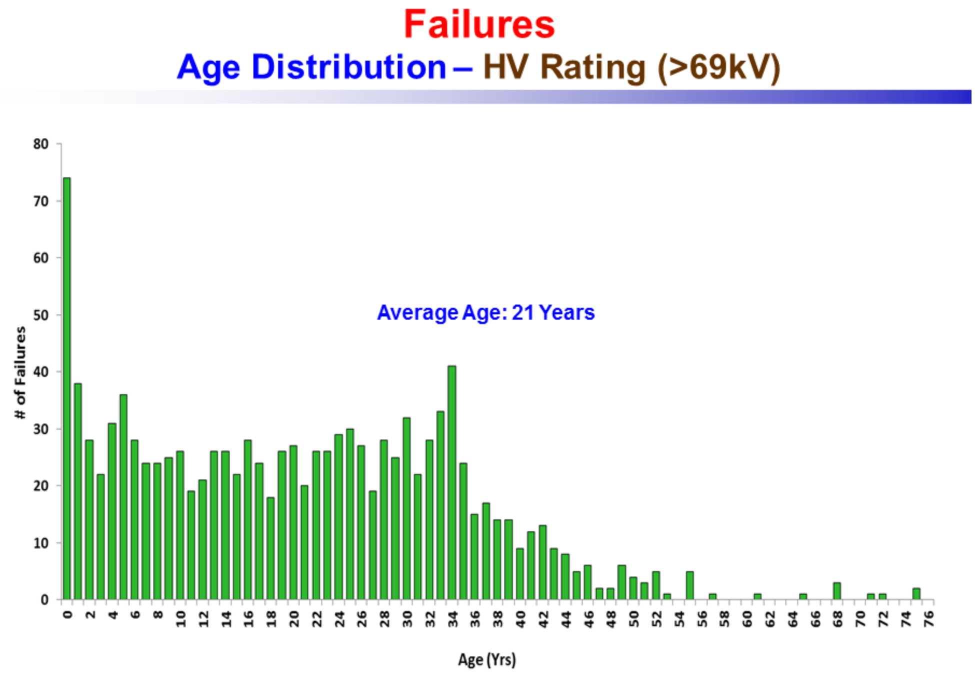


Figure 3-2
Age Distribution of Failed Transformers 69kV and Above

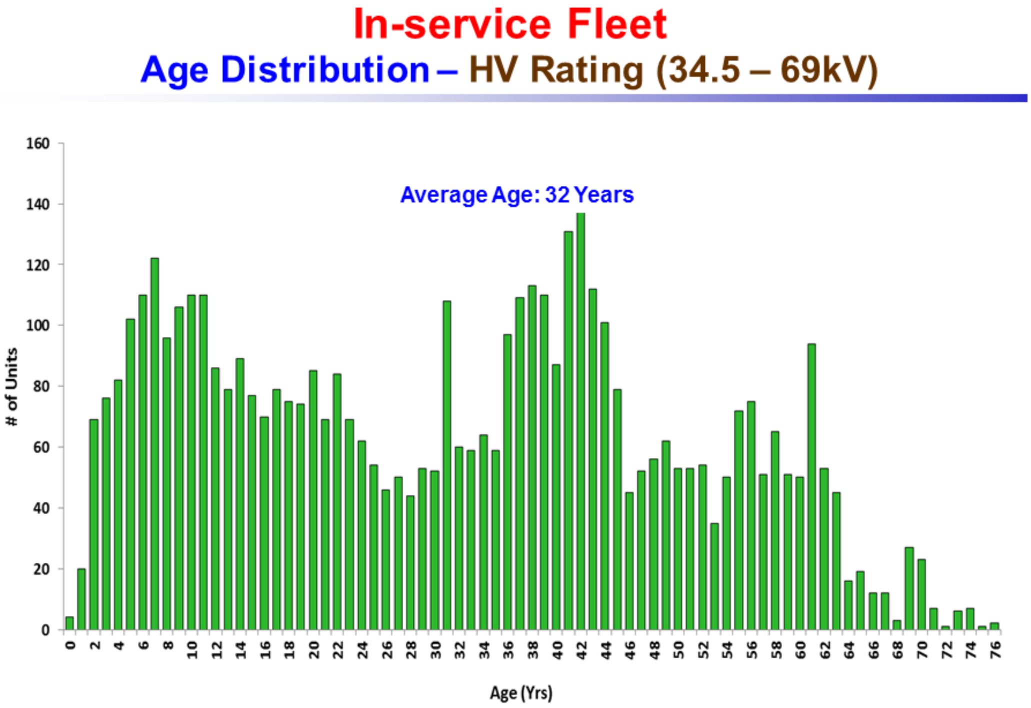


Figure 3-3
Age Distribution of In-Service Transformers 69kV and Below

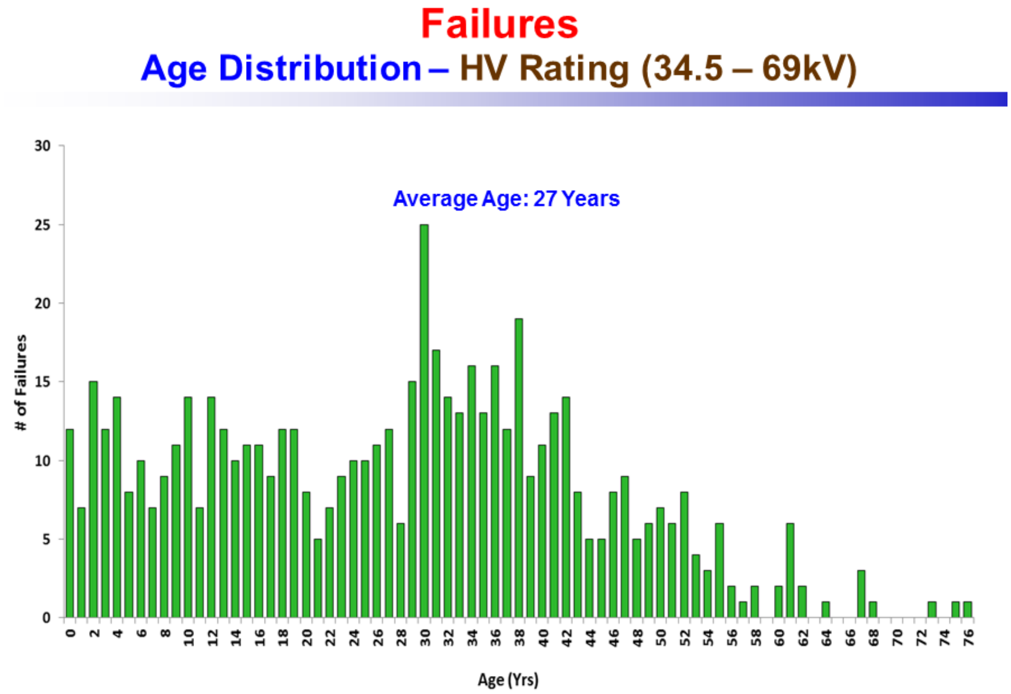


Figure 3-4
Age Distribution of Failed Transformers 69kV and Below

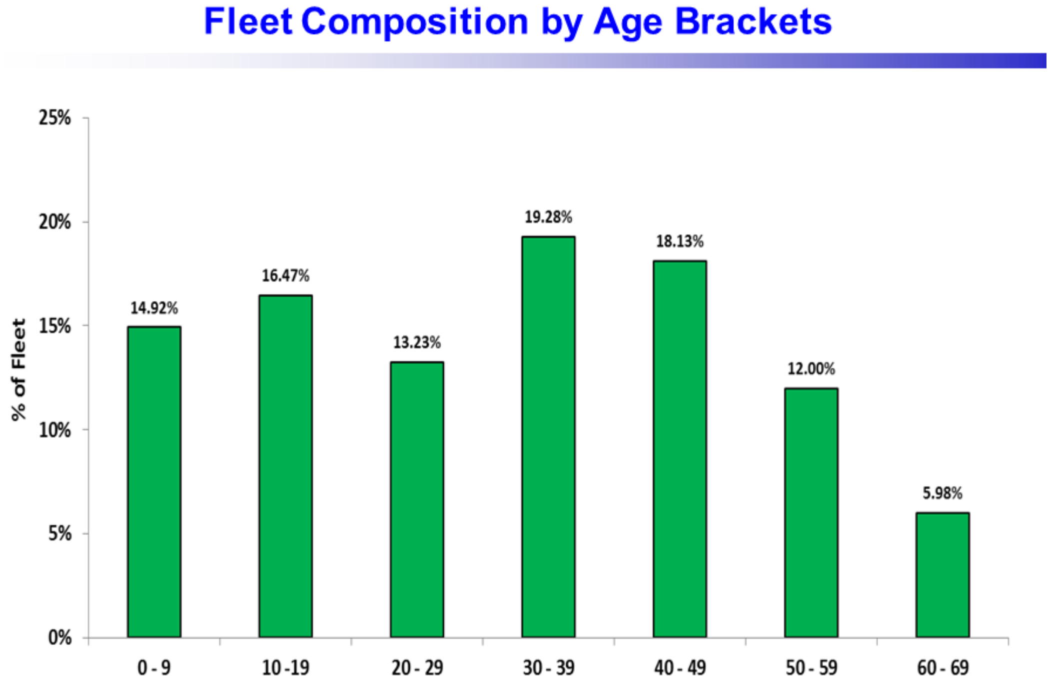


Figure 3-5
Fleet Composition by Age Brackets

Failure Details

In addition to failure dates, some utilities have supplied failure cause and/or failed component data. Analysis of this data can provide information useful for enhancing preventive maintenance and life extension programs. The failure data can also provide insights about type or vintage issues. Analysis of IDB failure records has also provided insights about failure causes and transformer component failure performance. This information can help maintenance managers develop proactive programs that may reduce maintenance costs and increase service life. Figure 3-6 shows the failure classification taxonomy.

In addition to identifying the failed component, failures are further classified as occurring *within the main tank* (e.g. winding) or at *another part of the transformer* system but external to the tank (e.g. bushing). Additional distinction is made between failure from causes *originating internal to the transformer* system (e.g. dielectric insulation breakdown), or causes *external to the transformer* system (e.g. stuck breaker or animal). Some example failure analysis results are provided
below.

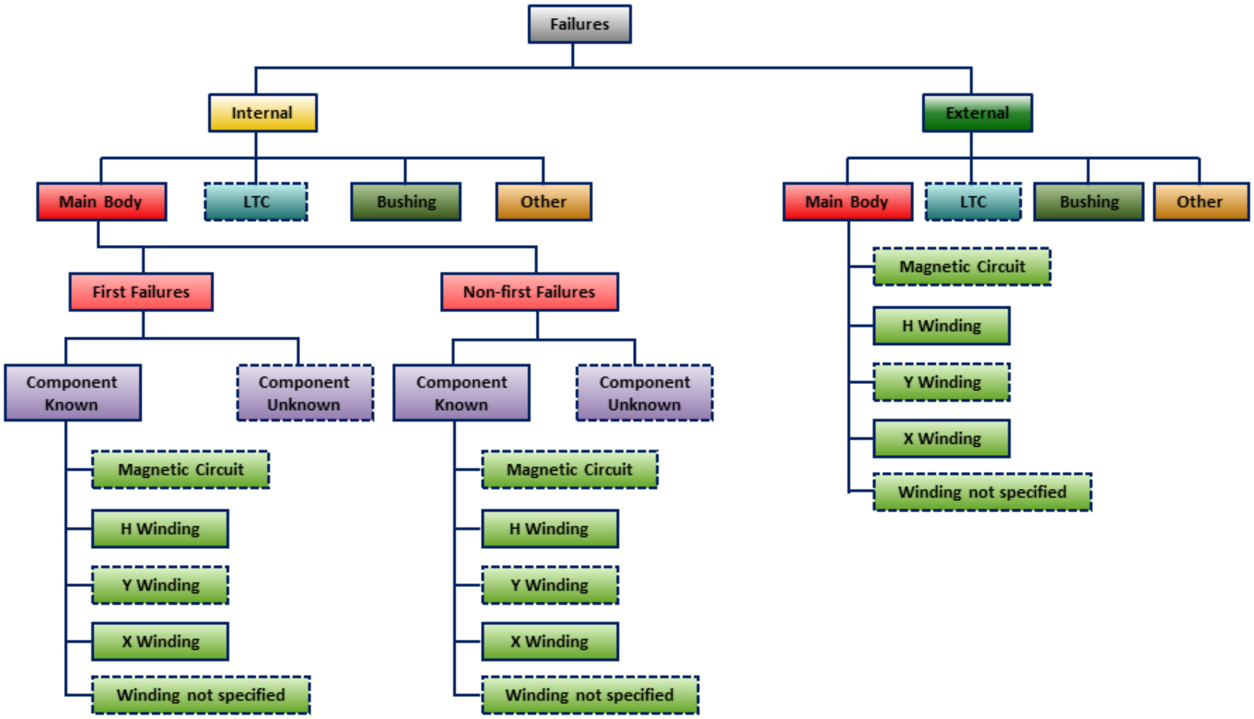


Figure 3-6
Failure Detail Classifications

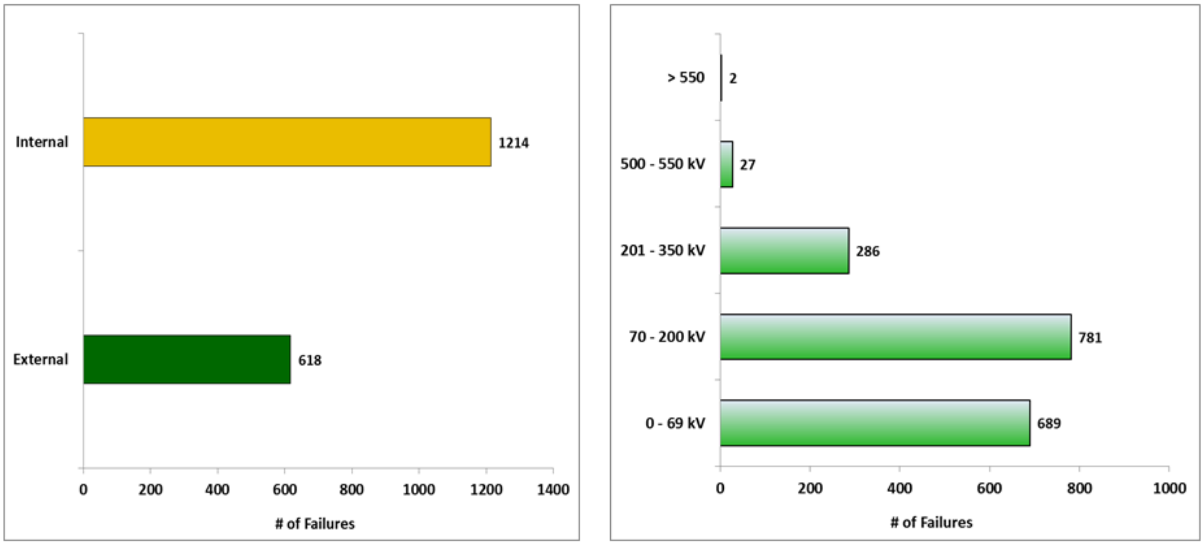


Figure 3-7
Transformer Failures: Internal, External and HV Rating

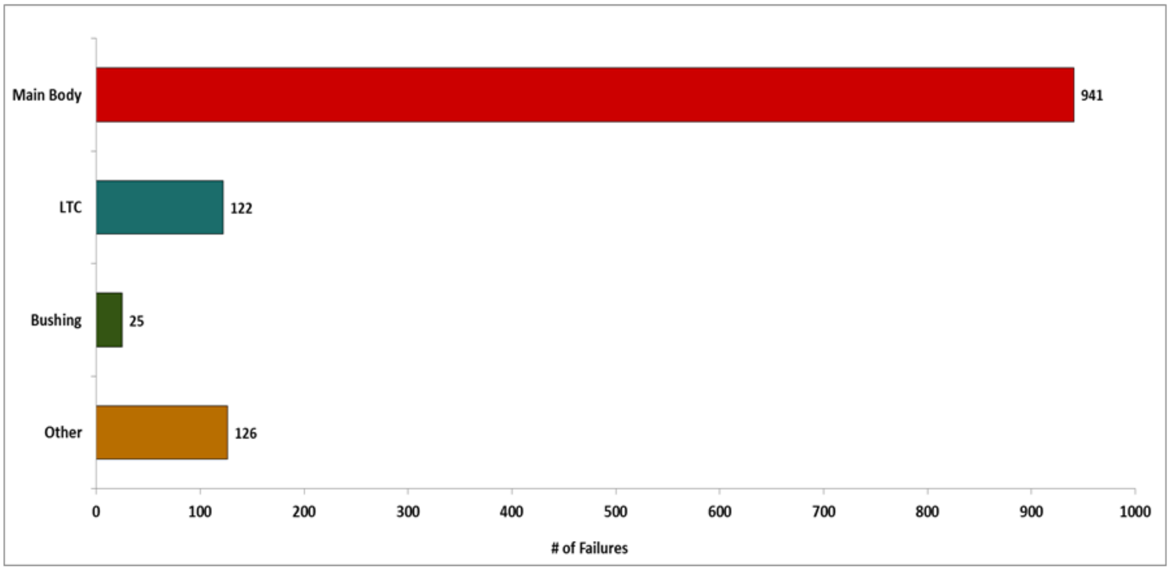


Figure 3-8
Internal Failures: Distribution by Subsystem

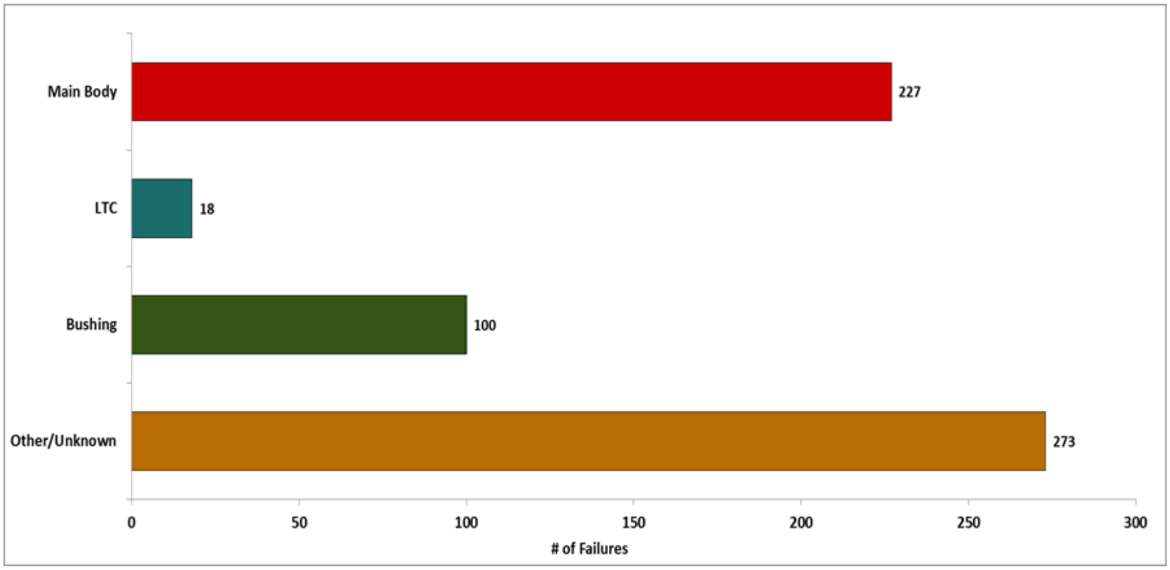


Figure 3-9
External Failures: Distribution by Subsystem

Failure Rate Analysis

Equipment performance data is necessary to be able to project equipment failure rates and costs as the equipment ages and its condition degrades. The key requirements – equipment failure models and equipment failure rates provide the motivation for developing an industry-wide performance database as a tool for planning and asset management.

Few utilities have a large enough population of like transformers from which they can develop accurate failure models. Most utilities have transformer populations made up of numerous models from a diverse set of manufacturers making it very difficult to predict the true expected reliability of any one specific model. Even when the population of a specific model is large, the utility many times finds that its operating experience and historical data are limited. EPRI's Transformer IDB is a collaborative effort to pool appropriate transformer operating and failure data in order to assemble a statistically valid population of many types of transformers.

Many utilities have adopted the philosophy that projected failure rates will continue at the same level as in the past. Unfortunately this assumption is based on failure rates consistent with being in the bottom portion of the "Bathtub Curve" and it ignores the adverse transformer fleet demographics that are a fact of life for a majority of utilities, as show in the demographic plots of the preceding chapter. The reality is that most utilities are operating significant numbers of transformers having ages in excess of 40, 50 and even 60 years, which implies failure rates consistent with those toward the back end of the "bathtub". Figure 3-10 illustrates the problem.

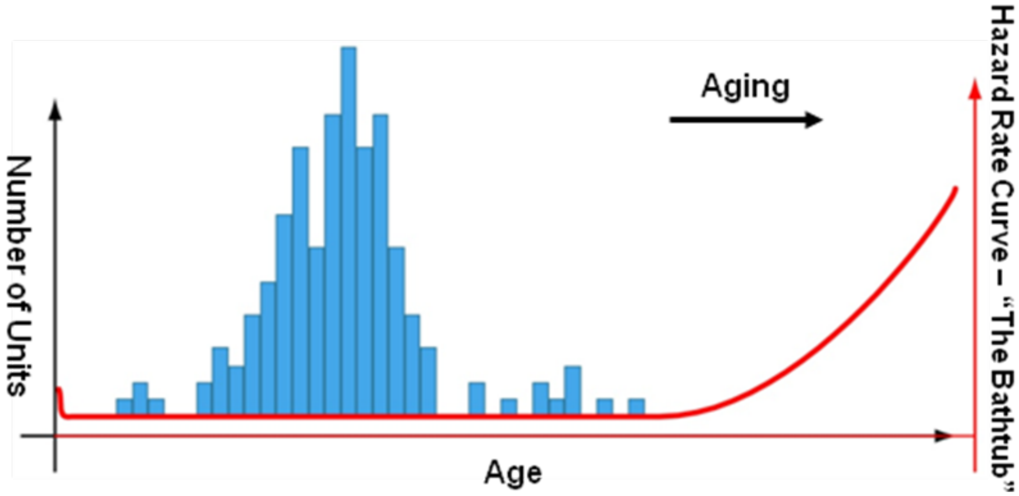


Figure 3-10
Relationship between Fleet Demographics and the Hazard Rate Curve

Mathematicians call the failure rate curve, or the back end of the bathtub, the hazard rate function. It defines the failure probability at each age bracket. Unlike the more familiar cumulative distribution that defines the probability of failure up to a given age, the hazard rate function defines the probability of surviving up to a certain age and then failing in exactly the next higher age bracket. The projected number of failures can be obtained by summing the products of the number of units in each age bracket times the value of the hazard rate function for that age bracket. Clearly, projecting a failure rate to be the same as in the past implies that the hazard rate function is constant (i.e. in the flat part of the bathtub curve) and that the number of transformer units in each age bracket is the same. Neither of these assumptions is valid for most utilities.

The situation is actually more complicated. There is no reason to believe that one hazard rate function fits all transformer groups. Even when just considering main winding age related failures parameter variations can be reasonably expected as a function of:

- Make
- Model
- Vintage
- Application

Figure 3-11 shows the more likely case. Preliminary results confirm, that transformer age related hazard rate curves vary for different population segments (e.g. auto vs. non-auto power transformers).

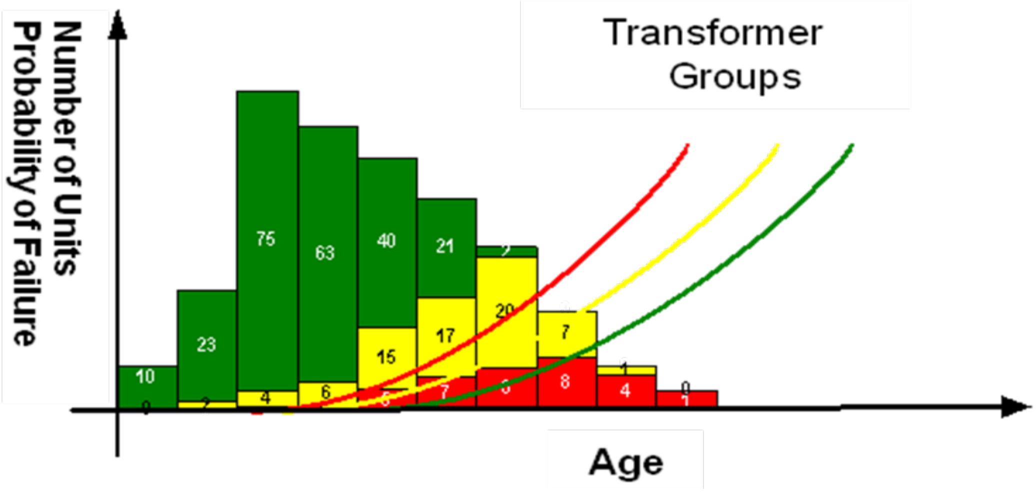


Figure 3-11
Different Hazard Rates for Different Transformer Groups

Clearly, one key application of the IDB is to assess whether this curve accurately describes historical transformer performance. If the bathtub curve applies to transformer life, what are the parameters of the curve—especially the wear-out portion of the curve? Do the curve parameters change with different transformer makes, models, vintages, and applications? Answering these questions is more important than ever as transformer fleets age and high replacement costs and uncertain lead times put more pressure on asset managers striving to meet high reliability standards.

We postulated increasing failure rate with age and therefore started with a simple Weibull distribution. This model is described by two parameters, a scale parameter and a shape parameter. It is assumed that these parameters may differ by transformer type or group. A Weibull plot for one IDB data set is shown in Figure 3-12. A good fit is observed.

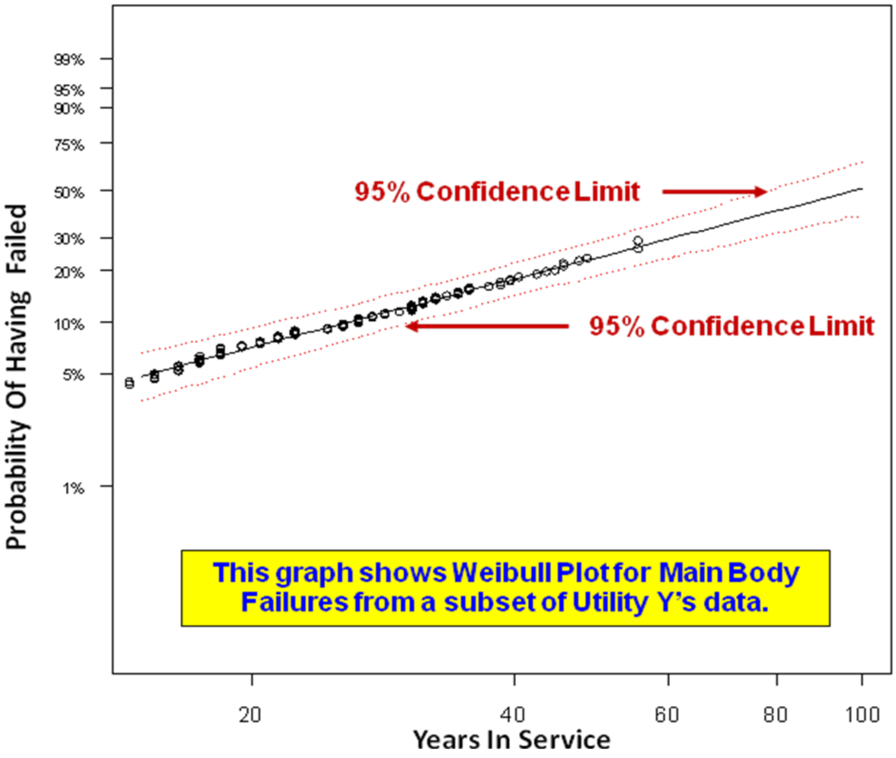


Figure 3-12
Weibull Plot for Utility Y Data

To estimate parameters of a model, the challenge is to find the parameters that make that model fit the data best. To compare among models, we find models which fit the data best, and decide if one or more models fit sufficiently better than the rest. Maximum likelihood estimation (MLE) and likelihood ratio (LRT) tests are used. MLE reflects goodness-of-fit metrics based on the likelihood (probability) of seeing the data given a particular model. In this case this means both the general form of the model and specific model parameter values.

The maximum likelihood estimates of the parameters are those values that make the observed data most likely to have happened. LRT compares two nested models, testing whether the nesting parameters of the more complex model differ significantly from their null values. LRT tests whether the extra goodness of fit to the data is worth the added complexity of the additional parameters. IDB statistical analysis is complicated by the large degree of truncation in the aggregated data and the different censor dates associated with the different utility data sets.

The analysis begins with a search for the best wear-out models to fit one utility's data. A second utility's data is analyzed to find its best models. The two sets of data are compared to assess similarity. If the two utilities' models are similar enough based on standard statistical tests, the two utility data sets are combined and the best models are found for the aggregated data. A third utility is then analyzed and compare to the aggregated models. The process continues, building a larger aggregated data set. As the set gets larger, the models' confidence bounds can be expected to improve.

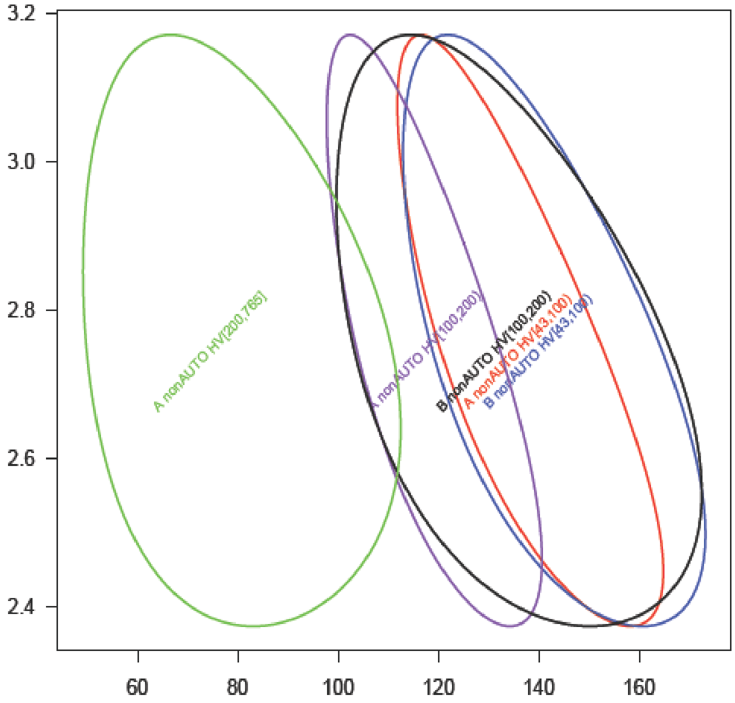


Figure 3-13
Confidence Areas for Weibull Shape and Scale Parameters

One result for a particular data subset is shown in Figure 3-13. This plot shows the 95% confidence areas for the Weibull scale and shape parameters resulting from the analysis of non-auto main body failures for utilities A and B. Note the significant overlap for the four ellipses to the right. This implies that a similar failure model would describe all four data subsets. The outlier to the left requires further investigation. The trend to a common hazard model will be explored as additional utility data becomes available in the industry-wide database and gets analyzed. It is anticipated that this will result in smaller ellipses, with tighter bound on the shape and scale parameters.

More recently, Bayesian analysis techniques have been explored. Bayesian analysis is a statistical procedure which estimates parameters of an underlying distribution, in our case a Weibull reliability function, based on the observed distribution given by the historical transformer data. The strength of the Bayesian approach is that, unlike for other methods where the possible parameter values to be determined could range over the entire positive value space; we can utilize engineering knowledge to bound the search space. We begin with a "prior distribution" based on the results of non-Bayesian observations of previous IDB data set performance. In the Bayesian paradigm, this current knowledge about the model parameters is expressed by placing a probability distribution on the parameters, the "prior distribution." As new data, that is failure observations, becomes available, the information contained regarding the model parameters is expressed in a "likelihood," which is proportional to the distribution of the observed data given the model parameters. This information from failure data is then combined with the prior distribution from engineering judgment to produce a new, upgraded probability distribution formally called the "posterior distribution" or updated distribution. Both Bayesian and Maximum Likelihood techniques will be used in future work to determine the most appropriate technique.

4

APPLICATIONS OF IDB RESULTS

One goal of the IDB work is to develop appropriate hazard rates for transformer subsets of interest. The hazard functions can be convoluted with the corresponding in-service population to provide forecasts of anticipated failures.

Utility Example 1

In Figure 4-1, an application example for a set of transformers from a particular utility provides the probability distribution of the number of failures in the next year based on a hazard rate determined from IDB analysis. Also provided are 95% confidence bounds on these probabilities. For example, the expected probability of having two failures in the next year is about 0.27. The black bars are the upper and lower 95% confidence bounds on this individual probability. That is, there is 95% confidence that the true probability is between about .28 and .21. There is essentially 0% chance of having greater than nine failures in the next year for this population. These results were computed using the appropriate hazard function and the transformer set demographic data. Such calculations can provide information useful for asset management and capital planning.

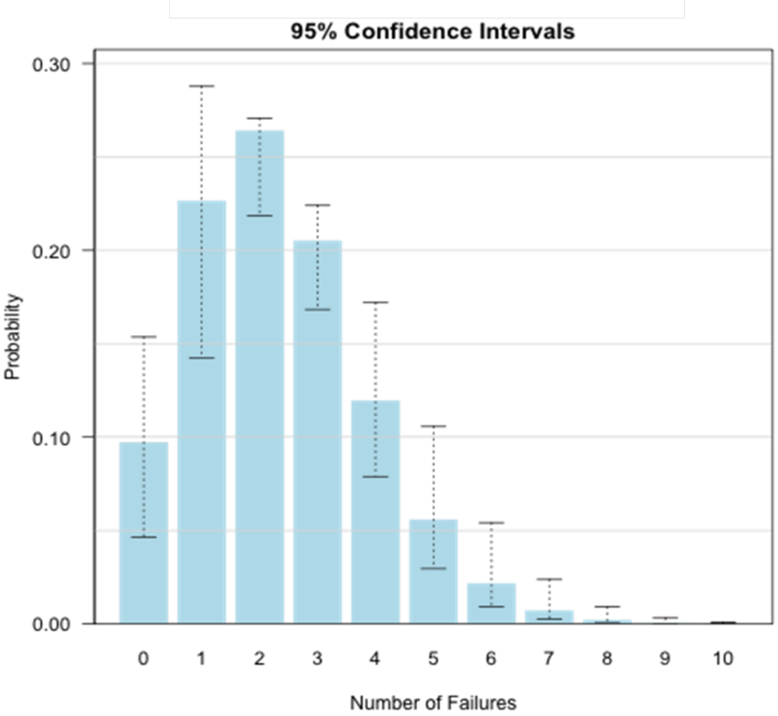


Figure 4-1
Yearly Failure Prediction

The above calculations can be presented in another form as shown in Figure 4-2.

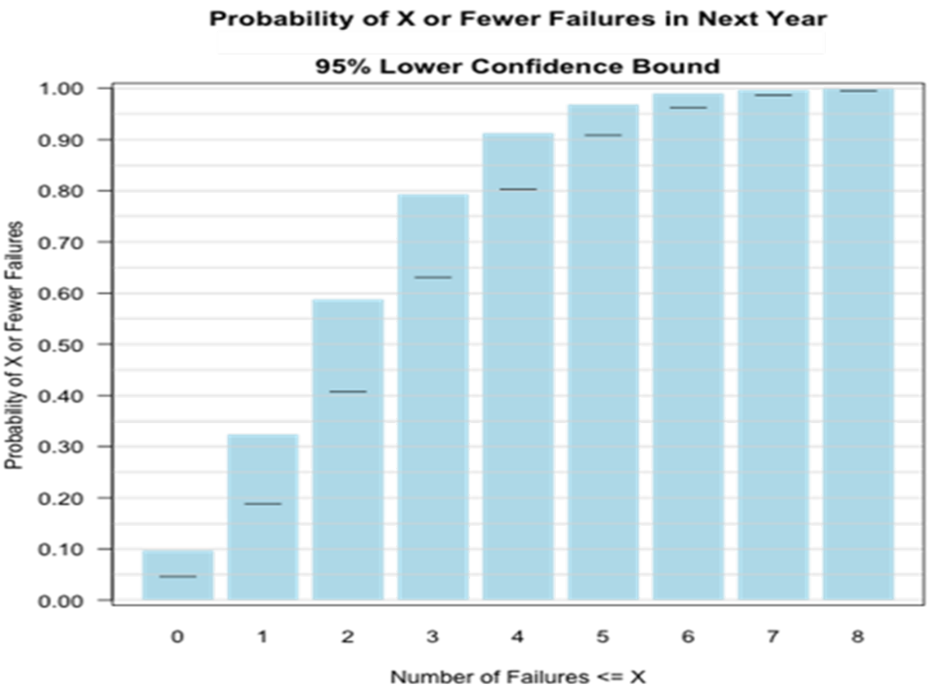


Figure 4-2
Maximum Number of Failures Prediction

This application example for a set of transformers from a particular utility provides the estimated probability of having a maximum number of failures in the next year. Also provided are the 95% lower confidence bounds on these probabilities. It was computed using the appropriate hazard function and the transformer set demographic data. For example, the "best" estimate of the probability of 6 or fewer failures is about 0.98. We are 95% certain that the probability of 6 or fewer failures is at least 0.96. The estimated probability of no failures is about 0.10. Such analysis provides utility managers with a quantitative method to associate risk with spares levels calibrated for the actual fleet demographics and hazard rate.

Utility Example 2

Utility A sought to develop a year-by-year prediction of the expected number of failures for the company's 67 kV family of substation transformers (approximately 400) for the next five years to help with capital planning and spares strategy. Because of their aging fleet, management was not willing to rely on historical failures.

The projections were based on advanced life analysis techniques developed in the IDB project. The analysis used IDB data and observations from similar transformers from other utilities and Utility A's in-service and historical data, which was mapped into the EPRI IDB data model with extensive utility interaction and support.

The analysis utilized data subsets derived from the larger utility data set within the IDB. These data consist of 67 KV class substation transformers that are currently in service, were retired before failure, or have failed. Repaired transformers, i.e. previously failed, repaired and returned to service, are not included in the analysis data set.

The analysis encompassed and accounted for four classifications of failure modes:

1. Internal main body failures,
2. Internal non-main body failures,
3. External main body failures,
4. External non-main body failures.

These distinctions are important to the failure analysis because engineering knowledge of transformer construction and operation indicates no reason why these four modes should have the same hazard function.

The project team used Bayesian survival analysis with appropriate utility data for each failure mode to determine hazard function for that mode. Based on experience with other IDB data sets and engineering judgment, modeling of transformer survival was further divided into two age groups, before and after transformer age 10, with infant mortality before age 10 and wear out after. The analysis results do show agreement with infant mortality before age 10 and wear out thereafter.

Analysis began with a "prior distribution" based on the results of non-Bayesian observations of previous IDB data set performance. In the Bayesian paradigm, this current knowledge about the model parameters is expressed by placing a probability distribution on the parameters, the "prior distribution." As new data, that is failure observations, becomes available, the information contained regarding the model parameters is expressed in a "likelihood," which is proportional to the distribution of the observed data given the model parameters. This information (from failure data) is then combined with the prior distribution (from engineering judgment) to produce a new, upgraded probability distribution formally called the "posterior distribution" or updated distribution. The calculation involves multidimensional integration of complicated functions and is computationally intense and a Markov Chain Monte Carlo, MCMC, method was used.

Figure 4-3 is a bivariate plot showing the prior shape, scale distributions and the update ones for main body wear-out. The gray points are random observations from the prior shape, scale joint distribution. The blue rectangle bounds the central 95% of this distribution. They represent prior, pre-data, knowledge. The blue dot is the “center” of prior knowledge.

The black dots represent a random sample of 9,600 pairs from the updated distribution of shape and scale given the information from the data as discussed above. The red “ellipse” contains the central 95% of the distribution, that is, where most (95%) of the pairs are located. The red dot is the mean of the upgraded knowledge, the expected values. The data has clearly upgraded knowledge of the shape and scale parameters as indicated by the much tighter distribution. From these upgraded shape and scale parameters failure predictions for currently in service transformers can be made.

The resulting eight failure functions and in-service population were utilized in a Monte Carlo simulation to predict the number of failures of the currently in service transformers. Figure 4-4 shows the predicted number of failures of the currently in-service transformers for each of the next five years.

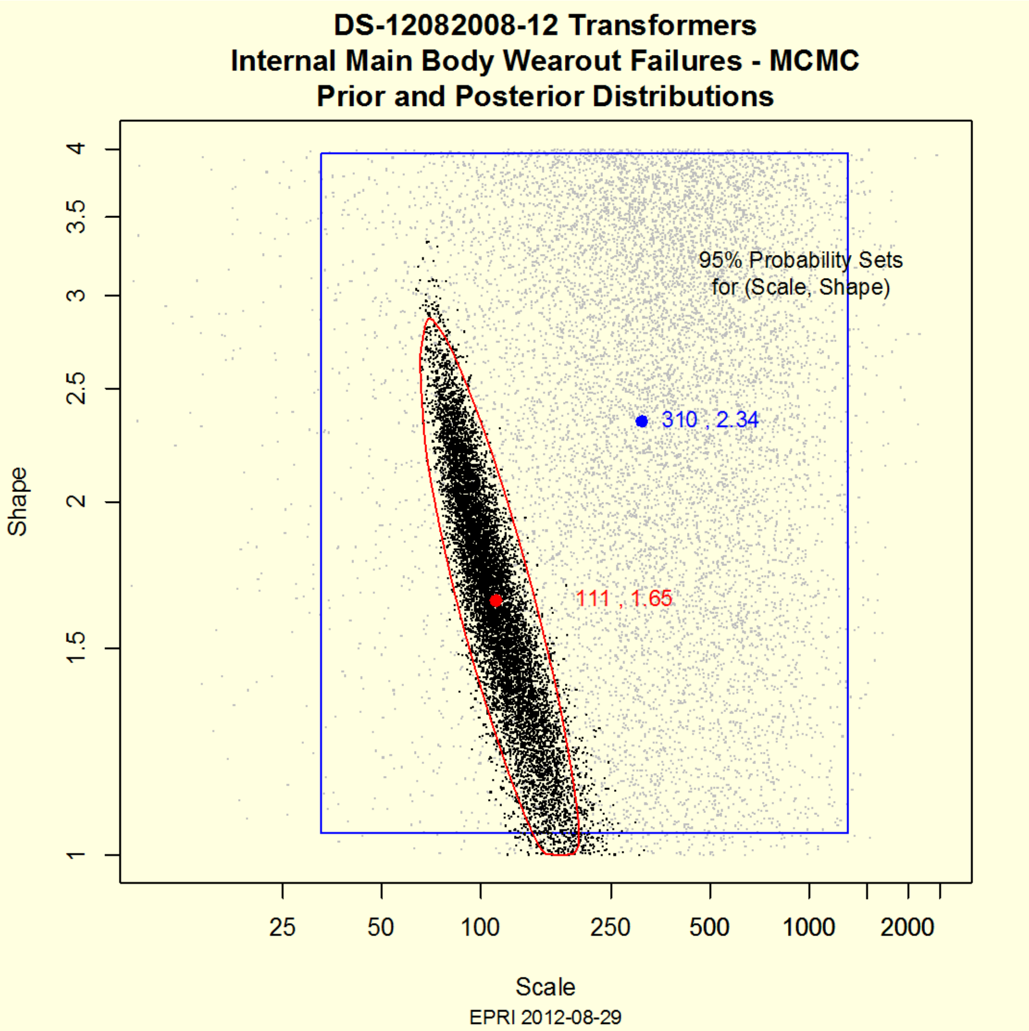


Figure 4-3
Bayesian Result for Main Body Wear-out Failures

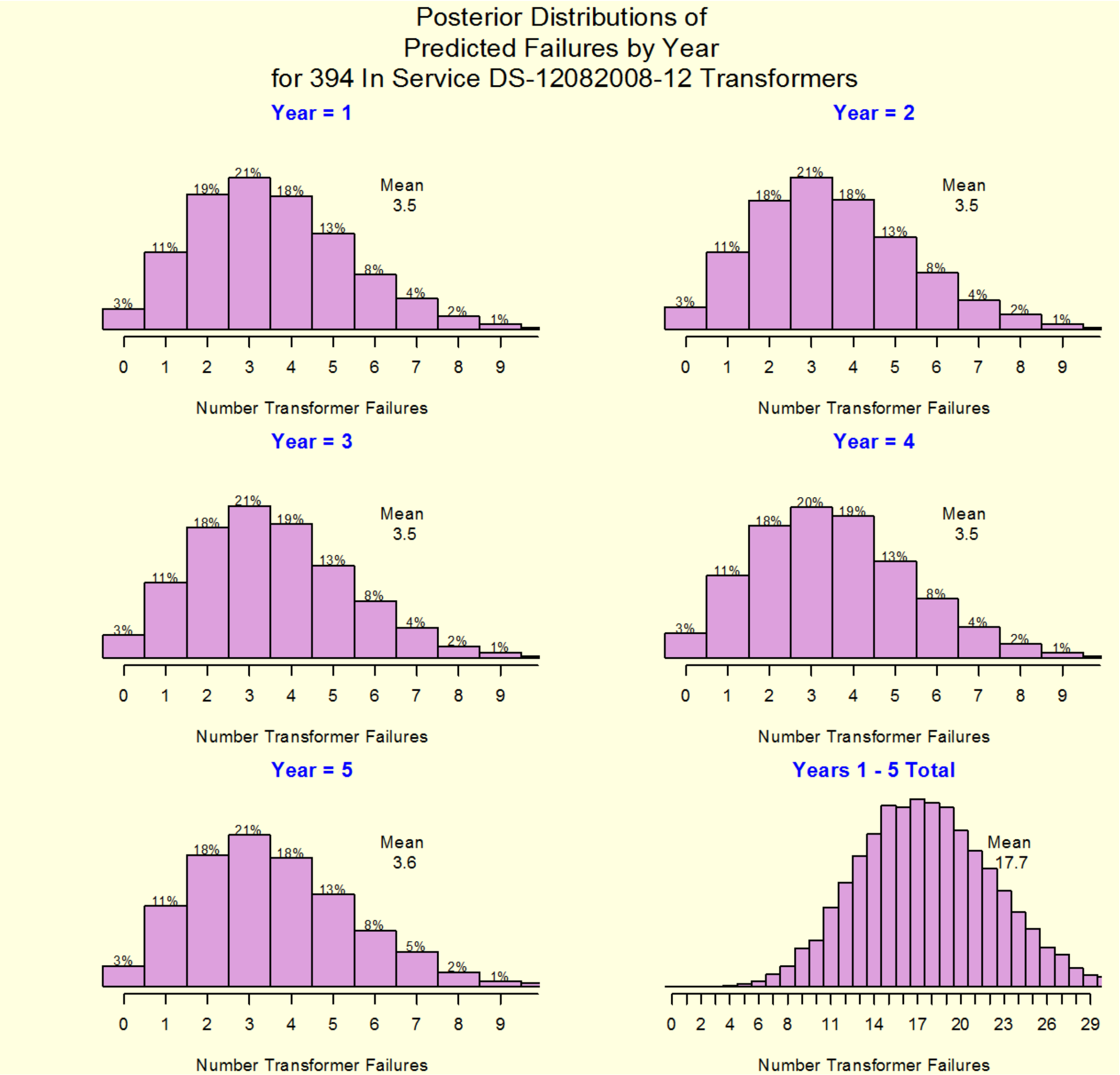


Figure 4-4
Predicted In-Service Transformer Failures for Each of the Next Five Years

Utility Example 3

Utility B management wanted to understand how its transformer fleet's failure rates compared with other utilities. EPRI's response was to use IDB data and develop several views, as follows:

- Yearly average age
- Fleet composition
- Yearly failure rate
- Running failure rate

The analysis started by developing a subset of the IDB that was composed of in-service and failed transformers with application and design characteristics similar to those of Utility B's fleet. Calculating a hazard function and associated confidence bands for each would not provide a very good basis for comparison. Therefore other metrics were used.

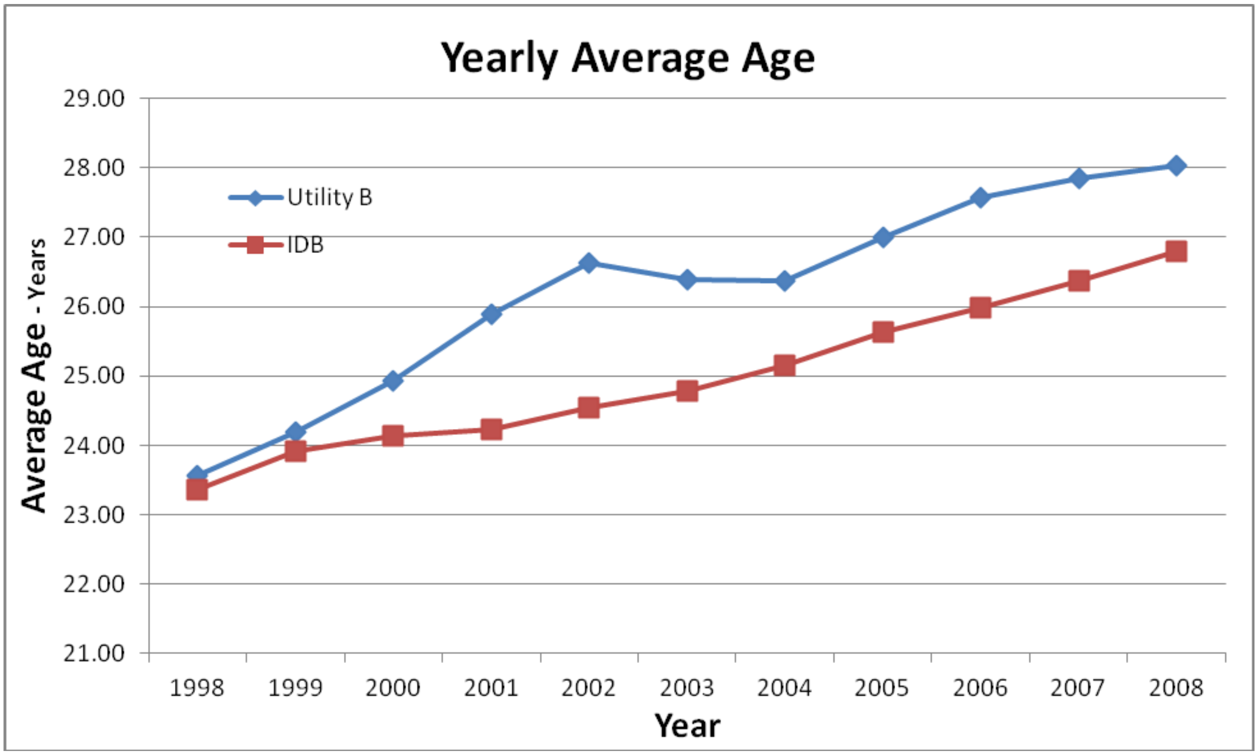


Figure 4-5
Yearly Average Age, Utility B and IDB

One important consideration was to understand how the two data sets compared in demographic distribution. Utility B has a fleet somewhat older than the comparable IDB subset. The analysis was conducted over the time period for which the utility had available reliable data.

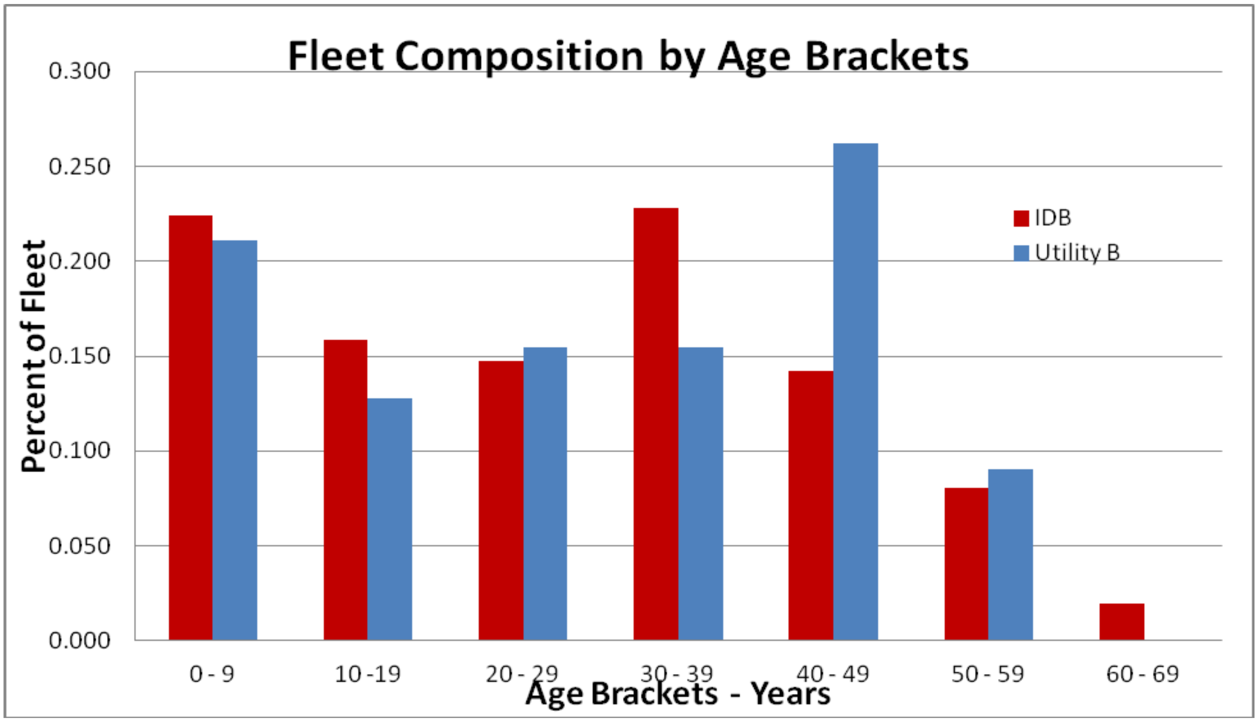


Figure 4-6
Fleet Composition by Age Brackets, Utility B and IDB

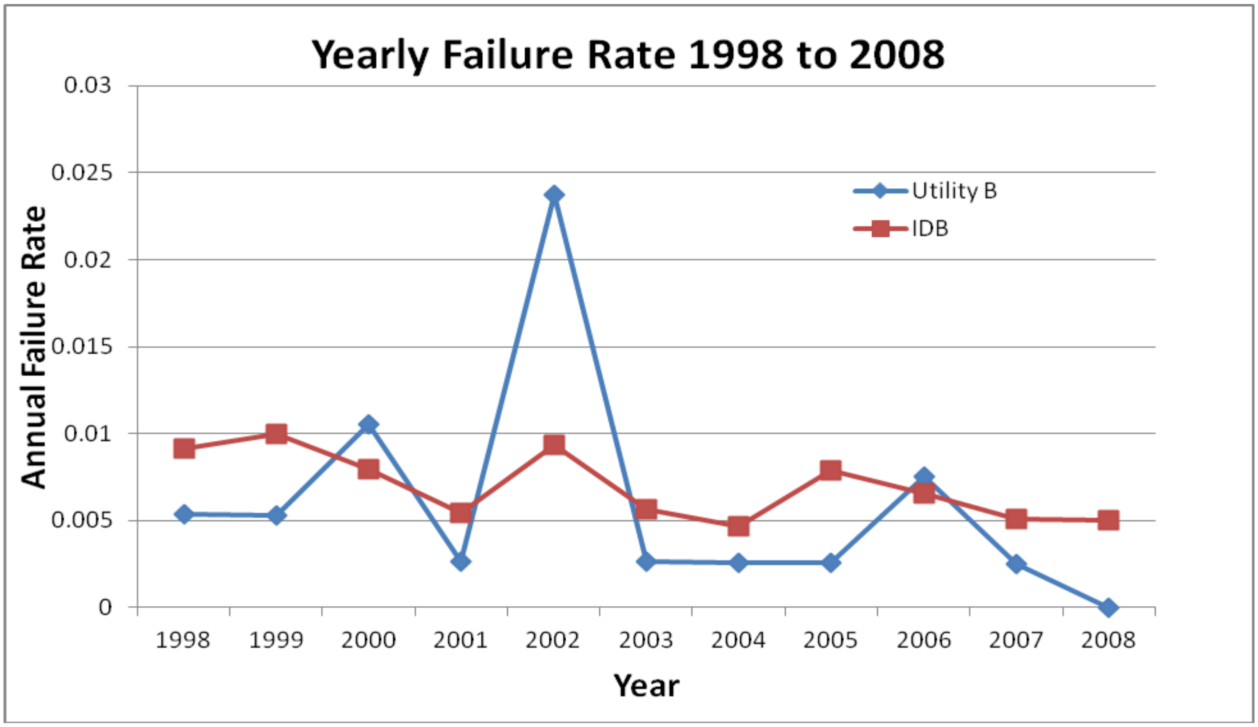


Figure 4-7
Yearly Failure Rate, Utility B and IDB

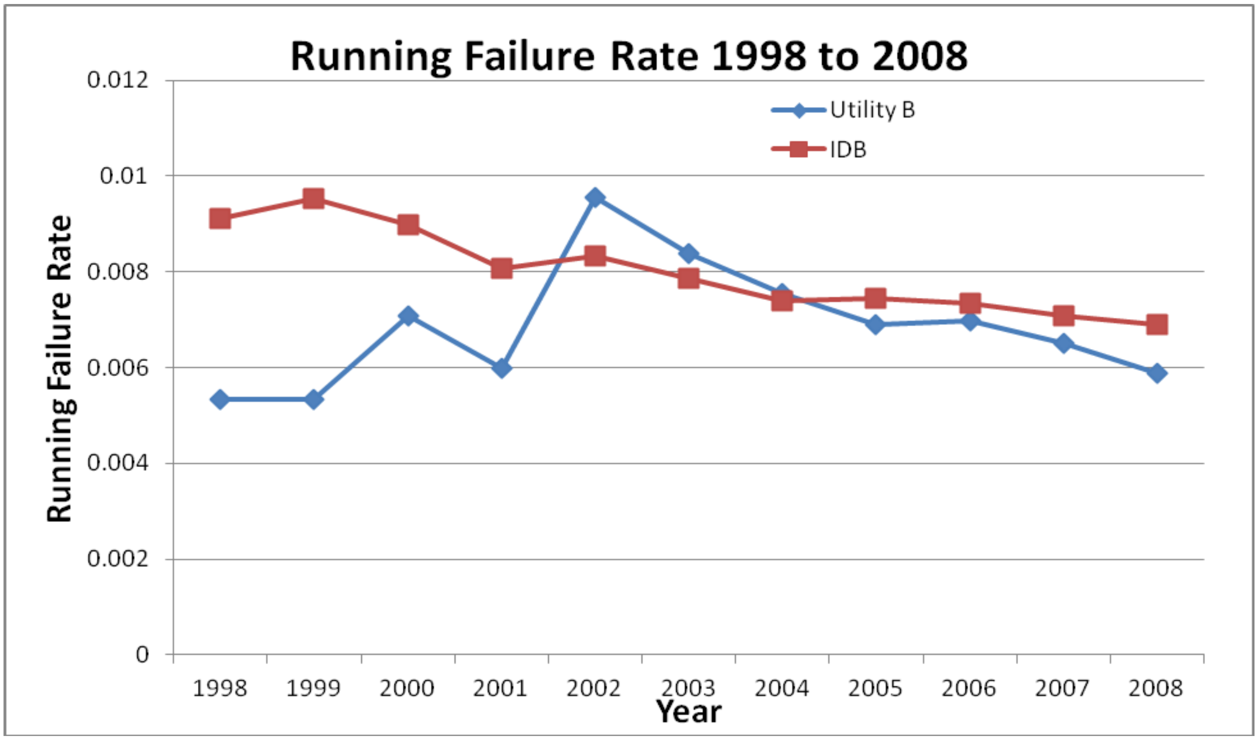


Figure 4-8
Running Failure Rate, Utility B and IDB

As would be expected, the yearly failure rate for the utility showed more variation than for the much larger IDB dataset. The running failure rate provides a better view of trends.

EPRI's analysis graphically showed that Utility B's power transformer fleet failure performance was better than that of the IDB aggregate despite having a somewhat older population.

General Analysis Conclusions

The IDB continues to grow and additional and improved analyses are planned but some preliminary observations appear reasonable. Based on the work to date, one may infer:

- Good Weibull model fit for age related failures in later life shows relatively gradual wear-out
- Non-auto and auto failure rates differ
- Non-GSU and GSU failure rates differ
- Non-repaired and repaired failure rates differ
- Different manufacturers may exhibit different failure rates

5

GOING FORWARD

EPRI's transformer IDB will provide utilities valuable insights and information to support maintenance repair and replacement decisions, and asset management decisions to minimize lifecycle costs of equipment replacement and maintenance, including failure costs.

Work to date has produced some valuable accomplishments:

1. Established a value consensus and assembled critical data mass
2. Developed practical data model
3. Developed data validation processes
4. Tested and identified applicable analysis techniques and methodologies
5. Produced promising preliminary results
    a. Descriptive failure statistics
    b. Aggregated data from different utilities
    c. Hazard rates that show age dependent wear-out
    d. Application of results to project anticipated number of failures

The IDB is an ongoing development and the insights, underlying methodology, approach and findings continue to be fine-tuned, enhanced and evolve as new data-sets are added and existing data reviewed.

A

DATA MODEL AND DATA COLLECTION

The transformer IDB requires a well-constructed data model to ensure that the best possible input data will be available for the analysis process and as a guide for utilities interested in developing enhanced data collection and in-house recording.

EPRI developed a prototype IDB architecture using the CIM (Common Information Model) naming conventions and developed specifications of the data model.

In the process of gathering data for the IDB it became clear that a protocol must be developed to standardize the data input. To that end a set of instruction were developed and reported in a technical update, *Industry-wide Substation Equipment Performance and Failure Database: Transformer Data Model and Data Collection.* EPRI, Palo Alto, CA: 2010. 1020010.

The report includes data submittal instructions and definitions for in-service transformers, failed transformers, and transformers removed before failure.

Data Fields

No.	Field Name	Field Description	Used for In-service Data	Used for Failure Data	Used for RBF Data	Data Entry Mode	Pre-defined List Values
1.	ID		X	X	X	Free form text	
2.	Operating Company/Region		X	X	X	Free form text	
3.	Sub-station		X	X	X	Free form text	
4.	Transformer Position		X	X	X	Free form text	
5.	Serial Number		X	X	X	Free form text	
6.	Manufacturer		X	X	X	Free form text/Pre-defined list	
7.	Auto Transformer		X	X	X	Pre-defined list	• YES • NO
8.	HV Winding Volts		X	X	X	Free form text	
9.	LV Winding Volts – 01		X	X	X	Free form text	
10	LV Winding Volts – 02		X	X	X	Free form text	
11	Tertiary Winding Volts		X	X	X	Free form text	
12	Top MVA Rating		X	X	X	Free form text	
13	No. of Phases		X	X	X	Free form text	
14	Date Manufactured		X	X	X	Free form text	
15	Date Installed		X	X	X	Free form text	
16	Date Failed			X		Free form text	
17	Date Retired				X	Free form text	
18	First Failure			X		Pre-defined list	• YES

No.	Field Name	Field Description	Used for In-service Data	Used for Failure Data	Used for RBF Data	Data Entry Mode	Pre-defined List Values
							• NO
19	Main Body Failure			X		Pre-defined list	• YES • NO
20	Failure Cause External			X		Pre-defined list	• YES • NO
21	Date Repaired			X		Free form text	
22	Date Replaced			X		Free form text	
23	Transformer Type		X	X	X	Pre-defined list	• Power • Shunt Reactor • Regulating • Phase Angle Regulator • Phase Shifting • HVDC Converter • Series Reactor • Other
24	Application		X	X	X	Pre-defined list	• Distribution • GSU • GSU Fossil • GSU Nuclear • GSU Hydro • GSU Combustion Turbine • Generation Station • Generation Station Auxiliary • Substation • Substation Auxiliary • Switching Station • Transmission Tie • Zig-Zag • Other
25	LTC Model – 01		X			Free form text	
26	LTC Model – 02		X			Free form text	
27	LTC Manufacturer		X			Free form text	
28	Core Type		X	X	X	Pre-defined list	• Core Form • Shell Form
29	Oil Type		X			Pre-defined list	• Mineral Oil • Non-mineral Oil

No.	Field Name	Field Description	Used for In-service Data	Used for Failure Data	Used for RBF Data	Data Entry Mode	Pre-defined List Values
							Other
30	Temperature Rise		X			Pre-defined list	55°/65° 65° 55° Other
31	Oil Preservation System		X			Pre-defined list	Nitrogen Pressure Regulator Conservator Bladder Conservator Sealed Nitrogen Blanket Other
32	Failure Discovered During			X		Pre-defined list	Installation Energization Normal Service Maintenance, Inspection or Test Energization After Maintenance Other
33	Failed Component			X		Pre-defined list	H Bushing X Bushing Y Bushing Leads-terminal Board H Winding X Winding Y Winding Tap Winding Connections Magnetic Circuit Shielding Insulation Core Insulation Fluid Circulation System Tank Heat Exchangers No Load Tap

No.	Field Name	Field Description	Used for In-service Data	Used for Failure Data	Used for RBF Data	Data Entry Mode	Pre-defined List Values
							Changer • Load Tap Changer • CTs • Auxiliary Equipment • Surge Arrestor • Oil Leak • PA Winding • Other • Unknown
34	Failure Resulted In			X		Pre-defined list	• Fluid Contamination • Excess Temperature • Dielectric Breakdown • Impedance Change • High Combustion Gas • Loss of Pumps • Loss of Fans • Tap Changer Malfunction • Fire • Expulsion of Insulating Fluid • Rupture of Tank • LTC Terminal Board Broke • Detailed Root Cause Available – see attached documentation • Other
35	Cause of Failure			X		Pre-defined list	• Electrical Design • Mechanical Design • Manufacturing • Inadequate Short Circuit Strength • Electrical Workmanship

No.	Field Name	Field Description	Used for In-service Data	Used for Failure Data	Used for RBF Data	Data Entry Mode	Pre-defined List Values
							• Mechanical Workmanship • Improper Storage • Improper Installation • Improper Maintenance • Improper Protection • Overload • Loss of Cooling • Operation Error • Transportation • Lightning • Earthquake • Animals • Vandalism • Sabotage • Bushing Flash Over • Bushing Contamination • Multiple Core Grounds • Static Electrification • Water Egress • Unknown • Other
36	Reason for Reporting			X		Pre-defined list	• Failure with Forced Outage • Failure with Scheduled Outage • Defect • Other
37	Transformer Disposition			X		Pre-defined list	• Rewound and returned to service • Repaired and returned to service • Repaired/Rewound and relocated • Repaired/Rewound to spare

No.	Field Name	Field Description	Used for In-service Data	Used for Failure Data	Used for RBF Data	Data Entry Mode	Pre-defined List Values
							• Scrapped • Not returned to service • Other
38	Repaired By			X		Free form text	
39	Repaired At (Location)			X		Free form text	
40	Relocated To			X		Free form text	
41	Replaced By (S/N)			X		Free form text	
42	Root Cause Determined			X		Pre-defined list	• YES • NO
43	Root Cause					Free form text	
44	Reason for Retirement				X	Free form text	

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